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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

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IDENTIFICATION AND INTERPRETATION OF BURIED SOILS

ROY W. SIMONSON

ABSTRACT. Examples of buried soils in the upper and lower portions of the Mississippi Valley are described, and their significance to gumbotil formation, to climates of the Pleistocene, and to loess deposition are discussed. The gumbotils of Iowa and adjacent areas seem to be chiefly B horizons of former Planosols developed under prairie vegetation. Previous estimates of time required for the formation of gumbotil seem high, on the basis of these studies. The nature of buried soils in the Upper Mississippi Valley suggests that they were formed in environments much like the present one. The geographic distribution of buried soils, insofar as it is now known, indicates that the pattern of forest and prairie on the former land surfaces was like that found by settlers in the past century, except that forest covered a slightly greater area. Soils buried by loess in the Lower Mississippi Valley are essentially the same as those derived from marine sediments in the Coastal Plain to the east and west. The wide distribution and common occurrence of these buried soils, originally formed under conditions of good drainage, seem conclusive evidence that the loess was of eolian origin. These buried soils also pose interesting questions as to the genesis of similar soils on the present land surface in the Coastal Plain.

Parts of buried soil profiles have long been of interest in Pleistocene geology, as evidenced by the studies of gumbotil (Kay and Apfel, 1928, p. 109-113) and the profile of weathering (Leighton and MacClintock, 1930). During recent years, buried soil profiles and horizons[1] have received increased attention, chiefly as stratigraphic markers and as possible keys to environments of the geologic past (Schonhals, 1950; Thorp, Johnson, and Reed, 1951; Schultz, Lueninghoener, and Frankforter, 1951, p. 28-33; Scholtes, Ruhe, and Riecken, 1951; Frye and Leonard, 1952, p. 19-25). As emphasized by Nikiforoff (1943, p. 198-200), however, the interpretation of buried soils is not simple. Understanding of the genesis of modern soils is far from complete, and the interpretation of buried soils is much more uncertain. Despite the difficulties, buried soil profiles and horizons can become more useful tools in geologic research, provided they are identified with care and interpreted with caution. To illustrate methods of approach and indicate limitations, this paper describes several buried soil profiles in the Mississippi Valley, relates them to modern soils, and draws inferences as to the environments in which they were formed. The relationships of certain buried soils to gumbotil and the time required for its formation are discussed, as is the significance of the buried soils to theories of loess deposition. Major kinds of horizons that might persist in recognizable form after a soil has been buried deeply are indicated. Discussion is restricted to buried soil profiles below the reach of current processes of horizon differentiation.

[1] The concepts of the soil profile and soil horizons are defined in the Soil Survey Manual (Soil Survey Staff, 1951, p. 123-250), as are other terms from soil science used in this paper.

INTRAZONAL SOILS,[2] UPPER MISSISSIPPI VALLEY

Formation of Nebraskan, Kansan, and Illinoian gumbotils[3] under conditions of poor drainage is generally acknowledged, but the gumbotils have seldom been interpreted as major horizons of former soils. In the classical studies of gumbotils in Iowa by Kay and his associates (1928, p. 109-113), a distinction is commonly drawn between "surficial soil" and gumbotil. A distinction between "fossil soil" and gumbotil is also made by Leighton and MacClintock (1930, p. 40) in the description of a profile of weathering in poorly drained Illinoian drift in Effingham County, Illinois. In some recent papers (Thorp, Johnson, and Reed, 1951, p. 3-10; Frye and Leonard, 1952, p. 22), the gumbotil has been considered a major horizon of a former soil profile, and its origin is more readily understandable in that setting.

During five years of soil surveys in Iowa, the author examined a number of gumbotil exposures described by Kay and Apfel (1928, p. 219-240) and by Kay and Graham (1943, p. 24-35). Not all the described exposures were examined, and some of those visited had slumped badly or were otherwise obscured. Gumbotil exposures were also examined during field consultations with Wood (1941, p. 326-344) in Adams County, Iowa. Subsequently, the author studied buried soils in Iowa, especially those formed from Kansan drift, in an effort to determine their relationships to modern soils (Simonson, 1941). On the basis of these various observations, it seemed clear that gumbotil was a major horizon of a former soil profile in a great majority of exposures. The place of gumbotil in a former soil profile can be demonstrated most easily by the description of a few typical sections. For this purpose, a buried soil in southern Iowa is described and the description of a gumbotil published by Leighton and MacClintock (1930, p. 40) is reinterpreted.

Buried Planosols[4] *in Iowa.*—Although they are less common than other kinds of buried soils, complete Planosol profiles were observed at seven places in six southern counties. Incomplete but otherwise similar profiles were noted in a number of additional places. All these buried Planosols were derived from Kansan drift and had been covered by loess, identified by Kay and Graham (1943, p. 157) as Peorian but now considered to be undifferentiated Wisconsin loess (Ruhe, 1952, p. 401). The complete buried profiles are exposed mainly in road cuts through flat divides between drainage systems. Deep cuts are uncommon in these flats, which are the highest parts of the landscape, and the number of exposures of buried complete Planosol profiles is therefore small.

[2] Intrazonal soils are those with distinct, genetically related horizons that reflect the dominant influence of topography, parent material, or time over the effects of climate and vegetation. The classification of soils is discussed in *Soils and Men*, U. S. Dept. Agr. Yearbook, 1938, p. 979-1001, and in Soil Science, v. 67, no. 2, 1949.

[3] The stratigraphic relationships of the various glacial drifts and of the loess deposits in the Midwest are shown diagrammatically by Thorp, Johnson, and Reed (1951, p. 4) and by Leighton and Willman (1950, p. 602).

[4] The nomenclature for great soil groups in the Mississippi Valley follows that outlined by Baldwin, Kellogg, and Thorp (1938) as modified by Thorp and Smith (1949). Recently proposed names for some of the great soil groups are also indicated in some instances. Planosols are defined briefly later in this section.

One of the buried soils from Kansan drift will illustrate the seven complete Planosol profiles observed in southern Iowa. The B horizon of this profile is considered by the author to be a representative example of Kansan gumbotil, as are the B horizons of the other six profiles. Covered by 6 feet of undifferentiated Wisconsin loess, the buried soil occurs in a roadcut 23 feet deep along the south edge of SE¼ NW¼ Sec. 23 T. 69 N. R. 24 W., Decatur County, Iowa (Simonson, 1941, p. 374-375). Referred to subsequently as a Yarmouth Planosol, the profile is described below, using terminology of the Soil Survey Manual (Soil Survey Staff, 1951, p. 173-250). The small letter "b" is included as part of a subscript identification in horizon designations to show that a profile is buried. Combined thickness of the modern soil profile and loess over the till is measured from the ground surface, whereas measurements of horizon depths are from the top of the buried soil profile.

Horizon	Depth—inches	Description
Wisconsin loess	0-72	Grundy silt loam, Prairie soil (Brunizem) developed from loess.
A_{1b}	0-3	Mixed light and dark gray friable silt loam containing some fine pebbles and coarse sand grains.
A_{2b}	3-15	Light gray friable silt loam with a few, distinct, fine reddish-yellow mottles; weak coarse platy structure; some coarse sand grains.
A_{3b}	15-18	Transitional horizon.
B_{1b}	18-24	Transitional horizon of dark gray clay mottled with reddish yellow. This is firm and plastic and has a moderate coarse blocky structure.
B_{2b}	24-36	Dark to very dark gray clay, faintly mottled with reddish yellow and strong brown. The mottles are fine to medium in size and are common. The layer is very hard when dry, plastic and sticky when wet, and has a weak very coarse blocky structure.
B_{3b}	36-54	Transitional horizon of olive to pale olive clay, faintly mottled with reddish yellow and brown. This seems massive in place but has a very weak very coarse blocky structure.
C_b	54-84	Leached and oxidized Kansan till, consisting of light yellowish-brown clay loam faintly mottled with reddish yellow.

In its morphology, this Yarmouth Planosol falls between Edina silt loam and Putnam silt loam, typical modern Planosols formed from loess under grass vegetation in southern Iowa and northern Missouri. Edina silt loam has been described by Ulrich (1949, p. 288-293) and Putnam silt loam by Whiteside (1944, p. 212-215). The general appearance of the buried soil, including colors and thicknesses of horizons, is similar to that of Edina silt loam, except for the thinner A_{1b} and thicker A_{2b} horizons. The colors and thicknesses of these two horizons in the buried profile are like those common to Putnam silt loam.

To characterize the buried Planosol more completely, certain laboratory analyses were made on samples of the individual horizons.[5] The results of these analyses are given in table 1. Part of the data are also shown graphically in figures 1 and 2 for comparison of this buried soil with Putnam silt loam and a buried Gray-Brown Podzolic soil.

The high degree of similarity between the Yarmouth and modern Planosols is as obvious from the laboratory data as it is in the morphology of the profiles. The maximum clay content within the profile is higher in the Yarmouth Planosol (63.2%) than it is in Putnam (57.7%) and Edina (52.3%) soils. The proportion of fine clay particles (less than 0.2 micron in diameter) in the B_{2b} horizon of the Yarmouth soil is slightly more than half the total weight of soil material (51.2%).

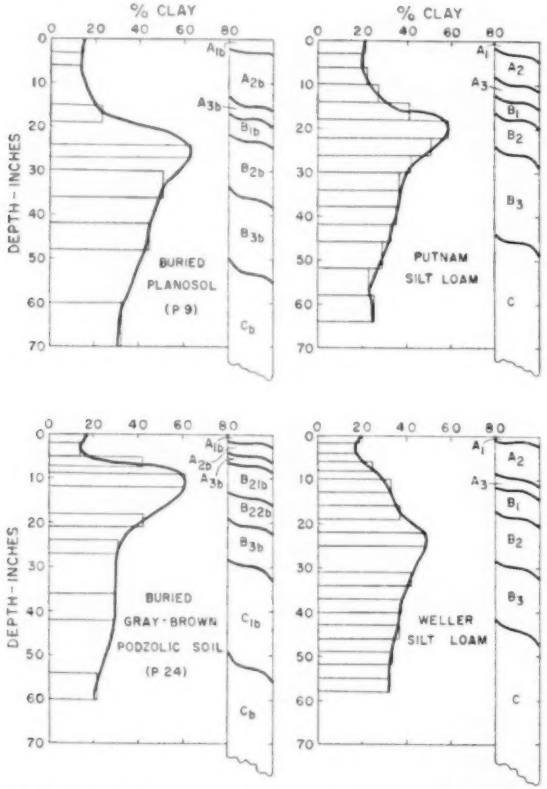

Fig. 1. Distribution of clay in profiles of two buried soils in Iowa and in two modern soils in southern Iowa and northern Missouri.

[5] Thanks are due L. C. Dumenil and George Stanford, Iowa State College, who made the analyses of this profile and of the buried Gray-Brown Podzolic soil considered in a later section.

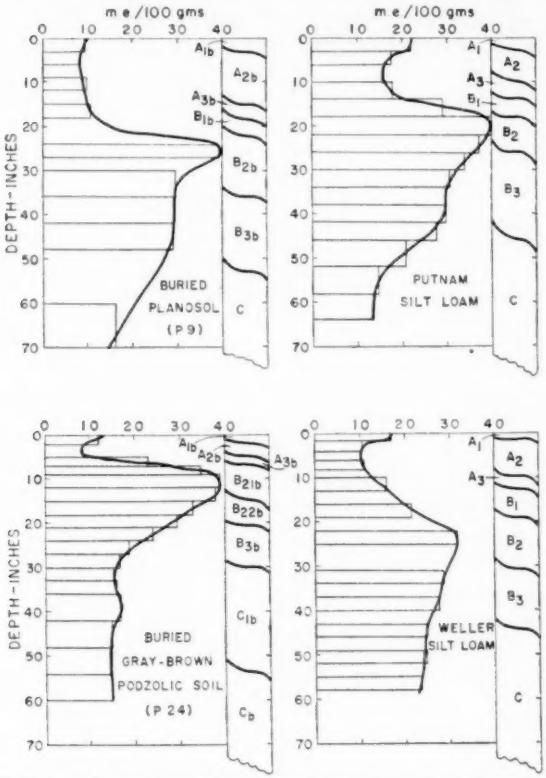

Fig. 2. Cation exchange capacities by horizons of two buried soils in Iowa and of two modern soils in southern Iowa and northern Missouri.

TABLE 1

Particle Size Distribution, Cation Exchange Capacities, pH, and Contents of Organic Carbon by Horizons in the Buried Profile of a Yarmouth Planosol, Decatur County, Iowa

Sample no.	Horizon	Sample depth (inches)*	Mechanical Composition** % Sand	% Silt	% Clay	% F. Clay	Exch. cap. me/100 gms	pH	% Org. C
1	Loess	60-72	1.0	69.7	30.0	15.7	21.8	6.3	0.23
2	A_{1b}	0-3	27.0	58.8	14.4	4.1	9.3	6.2	.17
3	A_{2b}	3-6	25.8	60.7	14.1	4.8	8.1	6.1	.18
5	A_{2b}	9-12	—	—	—	—	9.4	6.2	.21
7	A_{3b}	15-18	21.8	57.4	21.6	8.8	10.9	6.3	.18
10	B_{2b}	24-27	15.2	22.1	63.2	51.2	39.8	6.0	.22
12	B_{2b}	30-36	18.0	33.8	51.0	38.5	29.2	6.1	—
14	B_{3b}	42-48	26.7	29.8	45.3	33.0	28.8	6.4	.19
17	C	60-27	40.4	27.6	32.5	13.8	16.1	6.8	.12

* Depths are given for the loess sample from the present land surface and for the buried soil from the top of the profile.

** Particle sizes are as follows: sand 0.05-2.0 mm, silt 0.002-0.05 mm, clay $<$ 0.002 mm, and fine clay $<$ 0.0002 mm. Fine clay is reported as percent of the total weight of soil material, as are the other separates.

Because it was formed from drift rather than loess, the Yarmouth Planosol contains more sand in all horizons than do Edina and Putnam soils. At the same time, the curves for clay distribution in the three profiles are very similar (fig. 1) as are the curves for exchange capacities (fig. 2). Moreover, the clay minerals in the Yarmouth soils seem to be identical, on the basis of cation exchange capacities and differential thermal analyses (Simonson, 1941, p. 379-380), with those in modern Planosols formed from loess.

Careful study of field descriptions and laboratory data for the Yarmouth Planosol and the two modern Planosols underscores the similarities apparent at first glance. Moreover, the exposures of buried Planosols clearly show that the soils were formed on the highest flat divides in the landscape, as is now true for the Edina and Putnam soils. The three soils seem to be members of one great soil group, formed under similar environments in different geologic periods.

Buried Planosol in Illinois.—A second buried profile in which gumbotil is a major horizon is suggested by the description of a section in poorly drained Illinoian drift in Effingham County, Illinois (Leighton and MacClintock, 1930, p. 40). In describing the section and in their general notations for weathered zones in glacial drift, the authors distinguish surficial soil or fossil soil from gumbotil. The surficial soil or fossil soil seems to correspond approximately to the A horizon (including its subdivisions) as recognized by soil scientists. Thus, the surficial soil or fossil soil (Horizon 1 of these authors) is part of the soil profile in the concept of soil scientists. The relationships can be illustrated by the description of the section in Effingham County.

Geologic Horizon	Soil Horizon	Depth—inches	Description
—	—	0-34	Soil from loess above Illinoian till.
1	A_{1b}	0-7	Brown-black silt with red-brown spots; friable, non-plastic; containing sand and small pebbles. (This is called "fossil soil.")
1	A_{2b}	7-12	Dirty gray silt with streaks of gray and reddish brown; slightly more plastic than A_{1b} horizon. (This is called "fossil soil.")
2	B_{2b}	12-32	Dark gray clay, streaked with rusty brown, plastic and compact; sandy and pebbly, containing more pebbles than A_{1b} and A_{2b} horizons. (This is part of gumbotil.)
2	B_{3b}	32-62	Light gray clay with some streaks of darker gray; plastic but not very compact; very sandy, pebbly; pebbles are distinctly larger near base; matrix is splotched with yellowish brown which is more prominent in deeper part. (This is part of gumbotil.)
3	C_{1b}	62-68	Reddish-brown till; sandy, pebbly, silty; non-calcareous; slightly iron-cemented; friable, non-plastic; includes both large and small veins of gray material with large veins more sandy than general matrix, some faces black-coated. (This is leached and oxidized till.)
4	C_b	68-88	Brown calcareous till, iron-cemented like C_{1b} horizon; some horizontal lenses of sand. (This is part of oxidized but unleached till.)

Overlain by undifferentiated Wisconsin loess, the buried soil in Effingham County seems to have been formed during the Sangamon interglacial stage and will be referred to as a Sangamon Planosol. Tentative soil horizon designations for the layers described by Leighton and MacClintock (1930, p. 40) as far down as the oxidized but unleached till (Horizon 4 of these authors) are given below with slightly adapted descriptions.

The buried soil in Effingham County is identified as a Planosol because of the appearance, sequence, and thickness of the horizons. Although positive identification is not possible from the available data, this buried soil, if the gumbotil is included as its B_b horizon (B without any subscript refers to the B_1, B_2, and B_3 horizons collectively, whereas B_b refers to the B_{1b}, B_{2b}, and B_{3b} horizons collectively), seems almost identical in morphology with the Yarmouth and modern Planosols discussed earlier. Attention is called especially to the similarity in thickness of B_b horizons of the two buried Planosols. Moreover, the thicknesses of the gumbotils are comparable to thicknesses of B horizons in modern Planosols. Buried soil profiles which seem to be Planosols formed from loess and from drift have been described in Illinois by Norton (1930). Buried Planosol profiles formed from Illinoian drift and covered by Wisconsin loess are widely distributed in Illinois.[6]

GUMBOTIL AS A MAJOR SOIL HORIZON

In the two sample exposures described in the previous section, the gumbotil is the B_b horizon of a Planosol formed from glacial drift during an interglacial stage. The B_b horizon of the buried Planosol in Decatur County, Iowa, is considered to be Kansan gumbotil, whereas the Illinoian gumbotil in Effingham County, Illinois, is interpreted as the B_b horizon of a Sangamon Planosol. In all exposures examined by the author in Iowa, the Kansan gumbotil was part of the profile of a former Planosol. This is also the most common gumbotil in Jefferson and Van Buren Counties, Iowa, according to Schafer (1953) although a few Kansan gumbotil exposures were horizons in buried profiles of Humic-Gley soils (Wiesenboden). Thorp, Johnson, and Reed (1951, p. 10) suggest that the gumbotils are generally horizons of former Humic-Gley soils, especially in Kansas and Nebraska. Some of the buried profiles from Illinoian drift in Illinois seem to be Humic-Gley soils,[7] but members of that group are rare among buried soils formed from Kansan drift in Iowa. As identified in the past, gumbotil has included the B_b horizons of former Planosols and Humic-Gley soils. Available observations indicate that the gumbotil more often represents a former Planosol than a former Humic-Gley soil. Brief discussions of the nature and origin of Planosols and Humic-Gley soils should be helpful to a better understanding of gumbotils.

The Planosols are an intrazonal group of soils that have A_1 horizons of variable thickness underlain by light gray, usually platy A_2 horizons resting abruptly on dense B horizons which are plastic and sticky when wet, very hard when dry, and slowly permeable. They may be formed under either forest or prairie vegetation. Extensive in a belt extending eastward from southern Iowa and eastern Kansas to Ohio, Planosols are commonly developed

[6] Personal communication from Guy D. Smith.

[7] Personal communication from Guy D. Smith.

under humid to subhumid, cool-temperate to warm-temperate climates. They are formed in nearly level areas, usually well above the channels of streams. They are temporarily waterlogged at irregular intervals, and the profiles bear the marks of restricted drainage. Planosols do not, however, remain under water for extended periods of time.

The major process in the differentiation of horizons in Planosol profiles is the gradual accumulation of clay in the B horizon to the point where it becomes a "claypan." Part of this clay seems to have been formed in place, and part of it seems to have been moved down from the A horizon. In the early stages of development of the soils, the processes of horizonation seem to go more slowly under the grass than forest, other things being equal. As the differentiation of horizons proceeds and the "claypan" becomes pronounced, the rate of profile development decreases and finally must approach zero. On the whole, the Planosols formed under prairie vegetation are darker in color, especially in the A_1 and B_2 horizons, and have a thicker A_1 horizon than the Planosols formed under forest cover. For example, Edina silt loam has a much darker B_2 horizon than the Planosol formed under forest from the same loess in the same region. The darker color of the B_b horizon of the Yarmouth Planosol is considered evidence that the soil was formed under prairie vegetation.

The Humic-Gley soils (also called Wiesenboden) are an intrazonal group with thick, black to very dark gray A horizons, mottled gray to olive B horizons, and light-colored mottled C horizons. They are formed under grasses, sedges, and rushes where the water table stands above or well up in the soil for extended periods of time. Especially widespread in northern Iowa, southern Minnesota, and northern Illinois, Humic-Gley soils have been formed under a fairly wide range of climatic conditions, but they are most common in the humid to subhumid, cool-temperate zones. In appearance, the Humic-Gley soils differ from the Planosols in the greater thickness and darker color of the A_1 horizon and in the lack of an A_2 horizon. They also lack a "claypan" B horizon, but that lack may not be evident from the general appearance of the profile. As in the Planosols, the deeper horizons of Humic-Gley soils have drab colors of low chroma and are often mottled. If a Humic-Gley soil profile formed from fine-textured glacial drift were truncated by erosion, the remainder of that profile could look much like the deeper horizons of a Planosol. The buried Humic-Gley soils observed by Schafer (1953) seem to have been formed from fine-textured Kansan till, but the A_{1b} horizon has persisted in recognizable form.

With their genesis dominated by flat to depressed topography and the resulting restricted drainage, Planosols and Humic-Gley soils have limited usefulness as indicators of the climate prevailing during their formation. Although the modern examples of the two groups occur mainly in humid and subhumid parts of the temperate zone, the range in climatic conditions is still wide. When studied in conjunction with buried zonal soils formed during the same interglacial stages, however, buried Planosols and Humic-Gley soils can be very helpful in the reconstruction of former land surfaces, as will be indicated in later discussions.

Some geologic sections lack an A_b horizon between the gumbotil and the overlying loess, which might be considered an argument against the interpretation that the gumbotil is a major horizon of a former soil. In many such cases, evidence of dissection of the land surface prior to deposition of the loess may be found. Moreover, buried soil profiles, including Planosols as well as representatives of zonal groups, may be found in all stages of truncation, ranging from those with fairly complete sequences of horizons to those in which only a remnant of the B_b horizon remains. Wherever the relationships of incomplete buried profiles to former land surfaces can be determined, as is possible in many instances, removal of a former A horizon by erosion rather than original lack of one seems responsible for its absence from the geologic section.

Time required for gumbotil formation.—Duration of the Yarmouth interglacial stage was estimated by Kay (1931, p. 465) as 300,000 years, based on an initial figure of 25,000 years for post-Wisconsin time. Radiocarbon dating (Libby, 1952, p. 77-89) reduces the post-Wisconsin interval to approximately a third of the figure used by Kay, and the corresponding reduction in the Yarmouth interglacial stage brings it down to 100,000 years. This figure seems longer than necessary for the formation of gumbotil.

In the preceding section of the paper, much stress has been laid upon the similarity of gumbotil to the B horizons of modern Planosols in Missouri and Iowa. These similarities assume major importance in estimating the time required for the formation of gumbotil. The thickness of the Kansan gumbotil where it underlies an A_b horizon derived from glacial drift, as in the buried Planosol in Decatur County, Iowa, is of the same order of magnitude as the B horizons of modern Planosols. The Illinoian gumbotil in Effingham County, Illinois is a little thicker, but the difference is small. The quantities of clay in the solums (A and B horizons) of the Yarmouth and modern Planosols are essentially the same. Relative amounts of clay in the solums of the buried Planosol in Decatur County, of Putnam silt loam (Whiteside, 1944, p. 212-215), and of Edina silt loam (Ulrich, 1949, p. 288-293) are in the order of 35, 32, 29. If the comparison is restricted to the increased clay content of the solum over the C horizon, the relative figures in the same order are 12, 15, 12. Thus, it is not necessary to postulate a longer time interval for the formation of the gumbotil (B_b horizon of the buried Planosol) than for the development of B horizons in modern Planosols such as Putnam silt loam.

The time required for horizon differentiation in Putnam silt loam cannot be fixed with assurance. Assuming that the loess is of Wisconsin age, the differentiation of horizons in the Putnam profile could have started early during that stage and continued to the present time. Figures for the age of the Iowan-Tazewell loess in Iowa, oldest of the Wisconsin stage, fall near or above 17,000 years (Libby, 1952, p. 79). Thus, part of the loess in southern Iowa and northern Missouri could be more than 17,000 years old, but part of it is presumably younger. The younger part, having been deposited last, would certainly be a component of the Putnam profile. The time interval available for horizon differentiation is therefore much shorter than the esti-

mated duration of the Yarmouth interglacial stage, on the basis of an assigned Wisconsin age for the loess.

If the loess antedates the Wisconsin stage, a longer interval would have been available for differentiation of horizons in Putnam silt loam. This possibility cannot be established or eliminated with the information at hand. The massive deposits of Farmdale loess (Leighton and Willman, 1950, p. 603-604) in Illinois indicate active glaciers to the north prior to invasion of Iowa by the first of the Wisconsin glaciers. Whether significant deposition of loess occurred in southern Iowa and northern Missouri when Farmdale loess was being laid down in Illinois is not yet known. A post-Loveland pre-Wisconsin loess has been reported by Mickelson (1950) in western Iowa. The loess in southern Iowa and northern Missouri is continuous with loess resting on the Loveland formation further west. Conclusive evidence for the dating of the loess is therefore not yet available.

Other evidence of the time required for gumbotil formation consists of soils approaching Planosols in their characteristics but derived from Cary and Mankato drifts in north-central Iowa. One of these soils, Ames fine sandy loam (Meldrum, Perfect, and Mogen, 1941, p. 24-25), has a B horizon which is massive but not so thick nor so high in clay as Kansan gumbotil or the B horizon of Putnam silt loam. Furthermore, Ames fine sandy loam was developed under forest rather than grass vegetation, which seems to permit more rapid horizon differentiation, other things being equal. Despite all that, the very existence of gumbotil-like horizons in soil profiles formed from glacial deposits less than 10,000 years old suggests that time estimates for gumbotil formation are high.

The validity of comparisons of the soils from Kansan drift, Wisconsin drift, and loess rests on the assumption that the lithology of the three are similar enough to preclude marked differences in the rates of clay mineral formation. This assumption seems tenable with the information available, but it should be recognized as a limiting factor in the comparisons.

From consideration of the several lines of evidence, a postulated time interval of 30,000 years for the differentiation of horizons in Putnam silt loam seems a fair maximum. This estimate seems conservative in that it allows almost twice as long an interval as the age of some of the Iowan-Tazewell drift and four times as long as was required for evolution of Planosol-like soils on the most recent drifts.

The formation of Kansan gumbotil during Yarmouth time seems certain enough, but it is possible to question the assignment of an individual exposure such as that in Decatur County, Iowa, to a specific interglacial stage. This buried Planosol, which includes the gumbotil as the B_h horizon, lies immediately beneath loess now considered to be of Wisconsin age. Conceivably, soils formed from the Kansan drift during Yarmouth time could have been removed by erosion during the Illinoian glacial stage with subsequent formation of a Planosol, the present buried one, during the Sangamon stage. This seems improbable, however, on two counts. The first is the similarity among exposures of Kansan gumbotil, some of which underlie Illinoian drift (Kay and Apfel, 1928, p. 226-227). The second, which will be con-

sidered more fully in a later section of this paper, is the similarity in the kinds of clay minerals and in the maxima in clay distribution curves among the buried Planosols and other buried soils from Kansan drift, some of which lie beneath Loveland loess. From comparisons of all observed buried soils from Kansan drift, it seems most probable that the buried Planosol in Decatur County was formed during Yarmouth time. The soil must then have persisted on the land surface through the Illinoian and Sangamon stages before it was covered by loess, unless the identification of the latter has been in error.

Thick layers of gumbotil.—In some of the exposures in Iowa, the thickness of gumbotil is greater than that common to the B horizons of modern Planosols. Four possible explanations are advanced for these thick gumbotils, one or the other of which should be applicable to a given section.

Unoxidized and unleached till may be very similar in color, texture, and structure to gumbotil, as for example, the till from which Clarence soils have been formed in Illinois (Winters and Wascher, 1935, p. 619-621). Such till might mistakenly be identified as gumbotil. Errors of this kind have probably occurred, but they seem least important among the four possibilities.

If a buried Humic-Gley soil had been formed from fine-textured Kansan drift, the whole profile, exclusive of the A_{1b} horizon, and perhaps even part of the underlying drift might be taken for gumbotil. Except for the very dark A_{1b} horizon, the buried soil would be much like other gumbotils in appearance, and there would be a small change to the underlying drift. In such cases, the layer considered to be gumbotil might have included some underlying drift and might easily be several feet thick. Some of the thicker exposures of Kansan gumbotil are probably of this nature, though the author has not seen any.

Some exposures identified as Kansan gumbotil seem to consist of drift in the lower part and loess in the upper part, even though there is no evident break in the section. Quartz pebbles and sand grains are common in the lower part and lacking in the upper part. To explain such sections, two possible modes of origin are suggested.

If deposition of the loess were very slow, horizon differentiation in the soil profile formed earlier from the till and being covered by loess might keep pace with the additions of sediments. This has occurred to the extent of thickening the A_{1b} horizon severalfold in some buried Gray-Brown Podzolic soils in Iowa. The dark A_{1b} horizon in a buried profile in Taylor County, Iowa is 8 inches thick, as compared to normal thicknesses of 2 or 3 inches. The upper 6 inches of the A_{1b} horizon contains 1 percent or less of sand, whereas the bottom fourth of the layer contains 23.6 percent of sand, which has the same size distribution as does the sand in the underlying B_b and C_b horizons. Similar examples of thickening of the A_{1b} horizon are reported by Thorp, Johnson, and Reed (1951, p. 8) in Nebraska. If deposition of the loess were slow and continuous, the B horizon could "grow" upward, first into the former A horizon and later into the loess. Thus, the "gumbotil" would include more than the B_b horizon formed from till. It would be partly a "gumbotil" and partly a "gumboloess" with the two merging somewhere in the vertical section. This possible mechanism for the formation of thick

"gumbotils" needs to be tested by further investigation, but it provides one explanation consistent with what is now known about the genetic processes in the evolution of Planosols.

If the loess overlying the buried soil were of the proper thickness, the topography level but not too low, and the time interval sufficient, the B horizon of a Planosol formed from the loess might "fuse" with the B_h horizon of the buried Planosol. The B horizon of the more recent profile might form partly in the loess and partly in the B_h horizon of the older profile. Evidence of the merging of the B horizon of a buried Planosol from till can be observed in northern Missouri and southern Illinois where the loess mantle has a maximum thickness of approximately 3 feet on level interfluves. The merging of the B horizons of two or more profiles followed by another cycle of sedimentation is another mechanism which can be responsible for "gumbotils" a number of feet in thickness.

BURIED ZONAL SOILS, UPPER MISSISSIPPI VALLEY

Exposures of buried zonal soils,* which lack gumbotil layers, are far more numerous in the Upper Mississippi Valley than the buried intrazonal soils represented by Planosol and Humic-Gley profiles. Buried soils that were formed in undulating uplands with good drainage seem to be even more common in Kansas (Frye and Leonard, 1952, p. 19-25) and Nebraska (Thorp, Johnson, and Reed, 1951, p. 10-14) than in Iowa. Over the years, these soils have received far less attention than gumbotil, perhaps because many differ appreciably from the dominant modern soils in their respective localities. Yet their usefulness, especially in reconstructing the history of a region, is commonly greater than that of gumbotil.

Buried Gray-Brown Podzolic soils in Iowa.—A large majority of the exposures of buried profiles in Iowa were apparently formed under forest vegetation on well-drained sites. Thirty-two of the forty buried profiles examined by the author were considered members of the Gray-Brown Podzolic group. The morphology, clay distribution, and kinds of clay minerals form the basis for identification of the profiles as Gray-Brown Podzolic soils (Simonson, 1941, p. 376). Twenty-three of the thirty-two profiles were formed from Kansan drift, two from unidentified glacial drift, and seven from Loveland loess. These buried soils are widely distributed in the northeastern, east-central, southeastern, south-central, and southwestern parts of Iowa, all outside the region of Wisconsin drift. Exposures are most common in rolling to hilly landscapes where the modern soils are also members of the Gray-Brown Podzolic group.

One of the profiles formed from Kansan drift, presumably during the Yarmouth interglacial stage, has been selected to illustrate the buried Gray-Brown Podzolic soils in Iowa. Referred to in the remainder of the discussion as a Yarmouth Gray-Brown Podzolic soil, this buried profile is exposed in a roadcut a few rods north of U. S. Highway 30 in the SE¼ SW¼ Sec. 29, T. 83 N., R. 13 W., Tama County, Iowa (Simonson, 1941, p. 375-376). The buried soil is covered by 90 inches of Wisconsin loess which is calcareous in

* Zonal soils include those with well-defined, genetically related horizons that reflect the dominant influence of climate and living organisms in their formation.

the deeper part and from which another Gray-Brown Podzolic soil has been formed. A description of the buried profile is given below, with measurements of horizon depths recorded from the top of the buried profile. Terminology is like that used for buried Planosols in an earlier section of the paper.

Horizon	Depth—inches	Description
Wisconsin loess	0-90	Gray-Brown Podzolic soil (Fayette silt loam) formed from loess and calcareous loess (Wisconsin).
A_{1b}	0-2	Light gray to white, friable silt loam with weak medium platy structure and some black and brown iron concretions.
A_{2b}	2-5	White, very friable silt loam with moderate coarse platy structure; some sand grains and some iron concretions.
B_{1b}	5-7	Transitional horizon, more like one below.
B_{21b}	7-15	Strong brown to dark yellowish-brown clay which is plastic and sticky, has a moderate to strong medium subangular blocky structure and some brownish-black iron concretions.
B_{22b}	15-21	Mottled yellowish-brown and reddish-yellow clay with moderate to weak medium subangular blocky structure.
B_{3b}	21-30	Transitional horizon of mottled pale yellow, light gray and reddish-yellow clay loam with weak very coarse blocky structure.
C_{1b}	30-54	Leached and oxidized till consisting of clay loam which is dominantly pale yellow with few mottles, massive in place but friable when removed.
C_b	54-84	Oxidized but unleached till, a pale yellow to light yellowish-brown clay loam which is massive in place but friable when removed.

The morphology of the buried profile differs slightly from that of modern Gray-Brown Podzolic soils, although the sequence and thickness of horizons are alike. The A_{2b} horizon is paler and the B_{2b} horizon redder than typical. Pale colors of A_2 horizons of modern soils in the Upper Mississippi Valley are often associated with the segregation of iron oxides into concretions, as has occurred in the buried profile. The possible significance of redder-than-normal colors in the B_{2b} horizons of buried soils has been discussed by Scholtes, Ruhe, and Riecken (1951, p. 301-304), who described a second nearby buried profile in Tama County. The question of redder color and stronger chroma is considered later in this paper, but for the present, attention is called to the major similarities and the minor differences in morphology between buried and modern Gray-Brown Podzolic soils.

To characterize the buried Gray-Brown Podzolic soil more completely, certain laboratory analyses were made on samples of the individual horizons. The data obtained in these analyses are given in table 2, whereas some are also shown graphically in figures 1 and 2 for ready comparison of the buried Gray-Brown Podzolic soil with Weller silt loam. More complete data on the latter, a modern Gray-Brown Podzolic soil from loess in southern Iowa and

northern Missouri, are given by Simonson, Riecken, and Smith (1952, p. 125).

TABLE 2

Particle Size Distribution, Cation Exchange Capacities, pH, and Contents of Organic Carbon by Horizons in the Buried Profile of a Yarmouth Gray-Brown Podzolic Soil, Tama County, Iowa

Sample no.	Horizon	Sample depth (inches)*	Mechanical Composition** % Sand	% Silt	% Clay	% F. Clay	Exch. cap. me/100 gms	pH	% Org. C
1	Loess	80-90	4.2	81.0	12.6	5.3	21.7	8.0	†
2	A_{1b}	0-2	28.2	55.4	16.0	6.4	12.0	7.3	0.34
3	A_{2b}	2-5	33.7	52.2	13.8	5.7	8.5	—	.26
4	B_{1b}	5-7	20.9	38.8	41.8	19.4	22.7	7.1	.20
5	B_{21b}	7-9	—	—	—	—	34.5	7.0	.31
6	B_{21b}	9-12	23.1	17.7	61.1	46.8	38.3	6.8	—
7	B_{21b}	12-15	—	—	—	—	37.7	7.0	.25
8	B_{22b}	15-18	—	—	—	—	32.9	7.0	—
9	B_{22b}	18-21	36.5	22.5	42.1	33.5	29.2	7.1	—
10	B_{3b}	21-24	—	—	—	—	23.9	7.1	—
11	B_{3b}	24-27	46.2	24.9	30.5	20.4	18.5	7.1	—
12	B_{3b}	27-30	—	—	—	—	16.3	—	—
13	C_{1b}	30-33	—	—	—	—	15.1	6.8	.12
14	C_{1b}	33-36	—	—	—	—	16.0	—	—
15	C_{1b}	36-42	41.6	29.6	29.1	16.7	16.4	7.0	—
16	C_{1b}	42-48	—	—	—	—	14.8	7.0	—
17	C_{1b}	48-54	—	—	—	—	14.0	—	—
18	C_b	54-60	46.0	32.6	21.3	6.3	14.6	8.0	†

* Depths are given for the loess sample from the present land surface and for the buried soil from the top of the profile.

** Particle sizes are as follows: sand 0.05-2.0 mm, silt 0.002-0.05 mm, clay $<$ 0.002 mm, and fine clay $<$ 0.0002 mm. Fine clay is reported as percent of total soil material, as are the other separates.

† This layer was calcareous.

The buried Gray-Brown Podzolic soil contains more clay in the B_{2b} horizon, which also has a higher exchange capacity, than is common among the modern representatives of the group in Iowa. The maximum clay content in the profile of Weller silt loam is near 50 percent, as compared to 61.1 percent in the buried soil. The highest exchange capacity in any horizon of the buried profile is 38.3 milli-equivalents per 100 grams as compared to 33.5 milli-equivalents for Weller silt loam. In the maximum content of clay within the profile, Weller silt loam is similar to Edina silt loam. The two soils occur in the same general area, have been formed from the same kind of loess, and were developed over approximately the same period of time. Neither of the two has as much clay in the B_2 horizon as does Putnam silt loam in northern Missouri.

Gray-Brown Podzolic soils comprise a zonal group with thin dark A_1 horizons over light brownish-gray, platy A_2 horizons underlain by brown or yellowish-brown, finer-textured B horizons that grade into lighter-colored C horizons. These soils have been formed from a variety of rocks under broad-

leaf, deciduous forest vegetation in moist, cool-temperate zones. They are widely distributed in the northeastern fourth of the United States, exclusive of New England, being especially common where topography is undulating to rolling. Horizon differentiation in the profiles of Gray-Brown Podzolic soils is due in part to the gradual accumulation of clay in the B horizon, a process shared with Planosols. Part of this clay was moved down from the A horizon and part of it was formed in place. The stronger chromas of the B horizons in well-drained members of the group are due to the release of iron in the decomposition of silicates and its accumulation in the form of oxides. Along the southern margins of the region in which they occur, Gray-Brown Podzolic soils grade into the Red-Yellow Podzolic soils, major well-drained types of the southeastern United States (Simonson, 1949, p. 316).

The many similarities between the buried and modern profiles of Gray-Brown Podzolic soils are the basis for placing them in one great soil group. Attention has been called to the similarities in clay distribution curves, exchange capacities, and the general appearance and sequence of horizons. The types of clay minerals in the buried and modern soils are also the same, according to exchange capacities and differential thermal analyses (Simonson, 1941, p. 377-380). Consequently, it is believed that environmental conditions under which the buried profiles were developed were much like those under which the modern soils have been formed. In short, it seems that the buried Gray-Brown Podzolic soils were formed under forest cover in undulating to rolling uplands that were well drained.

Formation of the buried Gray-Brown Podzolic soil in Tama County, Iowa, during Yarmouth time may be questioned. The profile lies immediately beneath calcareous Wisconsin loess, and is not itself deeply leached of carbonates. Because of its stratigraphic position, several intervals must be considered as possible ones for its formation. The soil might have started to form during Yarmouth time and continued to develop during the Illinoian and Sangamon stages. Alternatively it may have formed during Sangamon time after dissection of the land surface and removal of any soil profile while the Illinoian glacier was advancing to the east. These alternatives cannot be eliminated but they seem less probable than the development of the soil during the Yarmouth interglacial stage.

Two lines of evidence support the original interpretation. Morphologically identical buried soils from Kansan drift underlie Loveland loess in western Iowa. This stratigraphic relationship provides convincing evidence that Gray-Brown Podzolic soils were formed from Kansan drift during the Yarmouth interglacial stage. The second line of evidence is the similarity to the Yarmouth Planosols in certain characteristics. The maxima and minima in clay contents and exchange capacities are almost identical for the buried profile in Tama County and the buried profile in Decatur County. With a maximum clay content of 63.2 percent, the B_{2b} horizon of the Yarmouth Planosol has an exchange capacity of 39.8 milli-equivalents per 100 grams. The B_{2b} horizon of the buried Gray-Brown Podzolic profile contains 61.1 percent clay and has an exchange capacity of 38.3 milli-equivalents. Minimum clay contents in the A_{2b} horizons are 14.1 and 13.8 percent. Similar relationships

exist among modern Planosols and Gray-Brown Podzolic soils of the same age formed from the same parent materials in southern Iowa. The glacial drift (C_b horizon) from which the two buried soils were formed seems to have been much the same, although the two profiles are some distance apart. For these reasons, it is concluded that the two soils were formed during the same interglacial stage.

The occurrence of several great soil groups formed from the same parent material is common in modern landscapes. Although formed at the same time, the soils differ because of differences in topography, drainage, or vegetation. Gray-Brown Podzolic soils, Prairie soils (Brunizems), and Planosols may all be found on a single farm in a number of places in southern Iowa at the present time. It also seems reasonable that a number of great soil groups were formed on the Kansan drift plain during the Yarmouth interglacial stage.

Superimposed buried profiles from glacial drift.—Three profiles, all of Gray-Brown Podzolic soils, are exposed in a cut along Iowa Route 129 about ½ mile north of Williamsburg in the northeast corner of Sec. 9 T. 79 N. R. 10 W., Iowa County, Iowa. Shown in figure 3, the cut has a depth of 16 feet divided equally between the surface mantle of loess and the underlying glacial drift. Two buried profiles formed from drift lie beneath the modern soil formed from loess. A brief description of the exposed section follows:

Depth (ft.)	Description
0-8	Gray-Brown Podzolic soil and loess (Wisconsin).
8-12	Upper buried Gray-Brown Podzolic soil from drift. This is lacking at the south end of the cut where the loess rests on the lower profile.
12-16	Lower buried Gray-Brown Podzolic soil from drift.

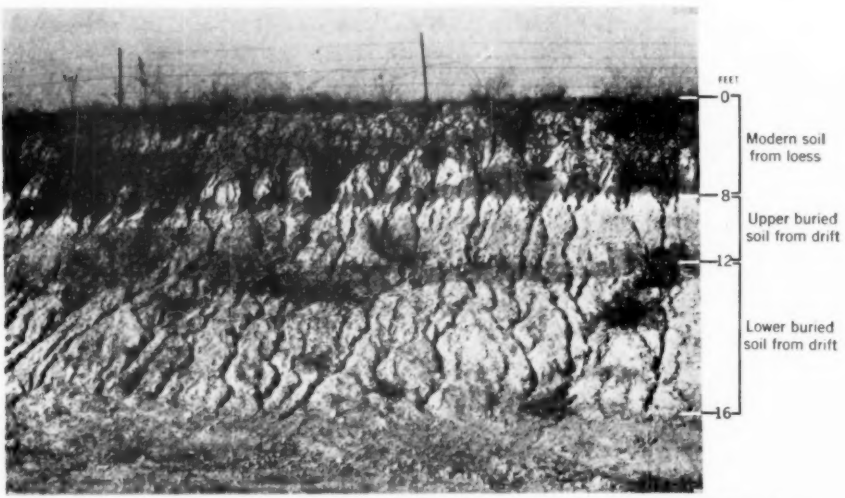

Fig. 3. Roadcut exposure of three superimposed soil profiles near Williamsburg, Iowa County, Iowa. The light-colored layer at the top of the upper soil is the A_{2b} horizon, whereas the darker layer immediately above is moist loess. The A_{2b} horizon of the lower buried soil is also moist and therefore appears dark.

The two buried soils are similar in morphology to the majority observed in Iowa. The upper buried profile has a distinct, light-colored A_{2b} horizon over a reddish-brown to yellowish-red B_{2b} horizon. This B_{2b} horizon is redder in color and lower in clay than is common among buried soils in Iowa. The texture of the B_{2b} horizon is sandy clay loam rather than sandy clay or clay. The lower buried profile has a less distinct but evident A_{2b} horizon over a prominent B_{2b} horizon of yellowish-brown sandy clay. This B_{2b} horizon is more nearly comparable in color and texture to those in the buried Gray-Brown Podzolic soils formed from Kansan drift elsewhere in Iowa. The C_b horizon of the lower buried profile is calcareous and contains lime concretions, as does the corresponding horizon of the buried profile studied in Tama County, Iowa.

There are two possible interpretations of the exposure near Williamsburg, Iowa. It lies far enough outside of the areas known to have been reached by the Illinoian, Tazewell, Cary, and Mankato glaciers to exclude the assignment of either drift to one of those stages or substages. It is near the margin of the Iowan drift (Kay and Graham, 1943, p. 100-102), however, and lies within the areas covered by the Kansan and Nebraskan glaciers. Thus, the lower drift could be considered of Nebraskan age and the upper drift of Kansan age. An alternative interpretation would assign the lower drift to the Kansan stage and the upper to the Iowan substage. The character of the profiles themselves do not provide adequate evidence for either correlation. The maximum content of clay in the upper buried profile is comparable to those in modern Gray-Brown Podzolic soils from loess, from Cary drift, and from Mankato drift. On the other hand, the hue of the B horizon is redder than is common in soils from sediments of known Wisconsin age. The maximum clay content in the upper profile is less than that common to buried soils from Kansan drift, at least those thought to have been formed during the Yarmouth interglacial stage, whereas the maximum in the deeper profile is not. Proper correlation of the two drifts near Williamsburg cannot be made with the evidence now at hand. Study of other exposures in the locality will be needed, together with more complete data on these and other buried profiles.

The two buried profiles are of special interest apart from their possible significance in correlation of the drift sheets. Distinct soil profiles covered by glacial drift seem to be rare; the one near Williamsburg, Iowa, is the only one thus far observed by the author. Furthermore, the three superimposed profiles demonstrate as many substantial periods of stability of the land surface, during each of which the soil was covered by forest vegetation.

CLIMATE AND VEGETATION DURING THE YARMOUTH STAGE

Inferences about the climate and vegetation of the Kansan drift plain during the Yarmouth interglacial stage are based on the resemblance of the buried soils to their modern equivalents. The pattern of vegetation on the former land surface is inferred from the distribution of the buried profiles. Better interpretations will be possible when the nature and distribution of the buried soils is known more completely, but certain inferences can be drawn from available observations. These indicate some of the uses and limitations of buried soil profiles in geologic research.

The nature and sequence of horizons in the buried Gray-Brown Podzolic soils provide strong evidence that the Yarmouth soils were formed under forest vegetation in a climate much like the present one in the Upper Mississippi Valley. The climate may have been a little warmer and drier than it is now, but the differences must have been small. The thickness of horizons, the kinds of clay minerals, and the amounts of clay in the buried soils are like those of modern Gray-Brown Podzolic soils with prominent horizons. The higher average chroma of the B_h horizons of the buried profiles, as compared to their modern equivalents, is the principal evidence in the soils themselves for a warmer climate during their formation. Coupled with the brighter B_h horizons are accumulations of calcium carbonate in the C_h horizons greater than those in the modern Gray-Brown soils in Iowa. This suggests the possibility of a slightly drier climate during the development of the buried soils.

The stronger chromas and redder colors of the B_h horizons of some buried soils, as compared to modern representatives of the same groups, have attracted much attention in recent years. Scholtes, Ruhe, and Riecken (1951, p. 304) state that the colors of the B_h horizons of buried profiles from Kansan drift are of higher chroma than the corresponding horizons of Gray-Brown Podzolic soils from Wisconsin loess. Frye and Leonard (1952, p. 23) mention the prevalence of reddish colors among buried soils in Kansas and discuss its possible significance. Thorp, Johnson, and Reed (1951, p. 12-13) stress this feature and ascribe it to the formation of the soils under warmer climates than now prevail. The fossil record in the Great Plains (Hibbard, 1952; Schultz and Stout, 1948, p. 567) indicates warmer climates than the present one during parts of the Pleistocene.

The stronger chromas and slightly redder colors of the B_h horizons of buried Gray-Brown Podzolic soils suggest that they are gradational toward Red-Yellow Podzolic soils, a zonal group in humid, warm-temperate to tropical regions, and hence were formed under higher temperatures than are now general in the region. Thus, it can be argued that the climate in Iowa during Yarmouth time was a little warmer than it is now, perhaps like the present one in southern Missouri, though that does not necessarily follow.

The alternative interpretations that reddish color or strong chroma may reflect either higher temperatures during soil formation or longer intervals of weathering are discussed by Frye and Leonard (1952, p. 23) and by Scholtes, Ruhe, and Riecken (1951, p. 304-305). In all probability, reddish color and strong chroma in the B horizons of soil are obtained by both routes. The genetic relationships among modern soils suggest that the factors of soil formation are interchangeable to some extent. The soil formed at any given spot is a function of the factors of climate, parent materials, topography, living organisms, and time. As a function of those factors, it could be obtained through different combinations of them. The product of a long interval of time and a low climate intensity could be the same as the product of a short interval of time and a high climatic intensity. Within some limits, as yet unknown, the same soil could be obtained by either route. Following that line of reasoning, reddish color or strong chroma could reflect a higher tempera-

ture in one profile and a longer period of weathering in another. Consequently, it does not seem necessary to postulate a warmer climate during Yarmouth time than at present in order to explain redder colors and stronger chromas. It may have been slightly warmer and drier, but the degree of similarity between the buried profiles and their modern counterparts is strong evidence against major climatic differences during their formation.

There are some indications that Gray-Brown Podzolic soils, extensive as they are in the northeastern fourth of the United States, are transitory even within the present environment. If they continue along their present routes of horizon differentiation, some of the Gray-Brown Podzolic soils seem scheduled to become Podzols, whereas others seem to be moving, albeit slowly, toward becoming Red-Yellow Podzolic soils. If this interpretation of trends is correct, a part of the modern group of Gray-Brown Podzolic soils would someday have colors and chromas of B horizons similar to those now found in many of the buried soils of the Upper Mississippi Valley but without any change in the present climate.

The distribution of vegetation over the plain in Iowa during Yarmouth time must have been much like that found by settlers moving into the upper Mississippi Valley during the past century. Apparently, forest covered the hilly to rolling uplands near major streams and extended for a distance toward the major divides. Buried Gray-Brown Podzolic soils from Kansan drift occur beneath Prairie soils (Brunizems) from loess in some places, which indicates a wider distribution of forest during the Yarmouth stage. Perhaps the forest was then invading the plain, as it was when settlement interrupted the invasion of the present landscape. If so, the invasion had progressed further during Yarmouth time.

The similarity in distribution patterns of buried and modern soils shows that forest vegetation did not cover the smoothest uplands farthest from the major streams on the Kansan drift plain during the Yarmouth interglacial stage. Planosols and Humic-Gley soils apparently occupied the flat divides in southern Iowa and northern Missouri during Yarmouth time, as they do in the present landscape. Consequently, it is inferred that prairie vegetation covered the flat divides during the earlier interval, as it did recently. Prairie vegetation seems to have extended out over the adjacent undulating uplands, especially those that lay considerable distances from a major stream. On the whole, the pattern of forest and prairie must have been much like the native vegetative cover of the present plain. The principal distinction seems to have been a wider distribution of forest on the Kansan drift plain during the Yarmouth interglacial stage.

BURIED ZONAL SOILS, LOWER MISSISSIPPI VALLEY

Buried soils are widely distributed in the lower Mississippi Valley but have received less attention than those in the northern half. Buried soil profiles and parts of profiles have been observed by the author in western Mississippi, Tennessee and Kentucky and in eastern Louisiana and Arkansas. Field notes collected by Wascher in the study of loess sheets in the southern Mississippi Valley indicate complete or partial buried profiles in at least one eighth and

more likely in one fifth of the 1200 observation sites. A few of these buried soils are described briefly in the report on loess sheets (Wascher, Humbert, and Cady, 1947, p. 389-396). Similar buried soils are also described briefly by Thorp, Johnson, and Reed (1951, p. 10-11).

The buried soils of the lower Mississippi Valley have been derived from a variety of geological materials, including sandstones, shales, limestones, loess, and unconsolidated marine sediments ranging widely in texture. All these buried soils have been covered by loess. Many of these profiles are truncated and incomplete, but the remaining sequence of horizons permits recognition of the soil in a large number of exposures. The buried profiles seem to be predominantly zonal soils, intrazonal soils being uncommon. This is in contrast to the upper Mississippi Valley where buried intrazonal soils are widespread. On the whole, however, the dominance of zonal soils among the buried profiles in the Mississippi Valley seems to parallel that among modern soils.

Buried Red-Yellow Podzolic soils from marine sediments.—Occurring widely in western Mississippi and Tennessee and locally in eastern Louisiana and Arkansas are complete and partial profiles derived from marine sediments and covered by loess. The sediments range in texture from sands to clays, with medium-textured materials commonly giving rise to buried zonal soils. One exposure, which includes several buried soils, occurs immediately west of the junction of State Route 35 and U. S. Highway 82 near Carrollton, Carroll County, Mississippi. The exposure, illustrated in figure 4, consists of a mantle of loess about 7 feet thick (including the modern soil profile) over buried soils formed from either coarse-textured or fine-textured marine sedi-

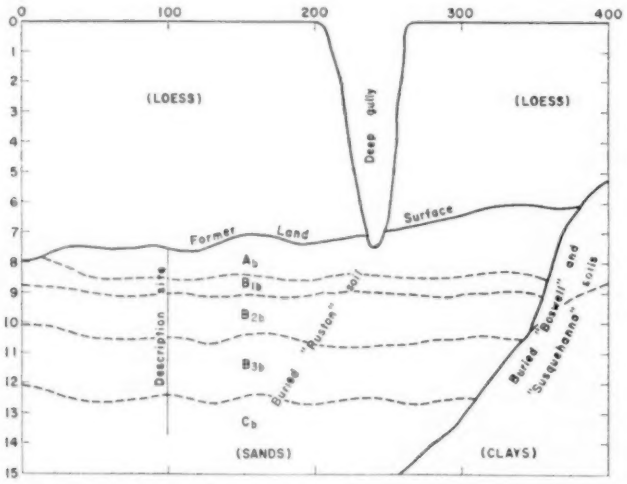

Fig. 4. Diagram of exposure of buried Red-Yellow Podzolic soils formed from marine sediments and covered by loess near Carrollton, Mississippi.

ments. Prepared to scale, the diagram[9] shows the horizontal profile variations in one of the buried soils. It does not include the whole exposure, which is 600 feet long and 20 feet deep at some points. A detailed description of the buried profile at the site identified in figure 4 is given below, following the terminology and conventions used above for buried Planosols and Gray-Brown Podzolic soils. Referred to in the diagram as a "buried Ruston soil," the profile seems identical with the typical representatives of the Red-Yellow Podzolic group of the southeastern United States. Combined thickness of the modern soil profile and the underlying loess is measured from the present land surface, whereas thicknesses of horizons are measured from the top of the buried profile.

Horizon	Depth—inches	Description
—	0-84	Grenada silt loam and underlying loess, a yellowish-brown (10YR 5/6) silt loam.
A_b	0-10	Yellowish-brown (10YR 5/6) fine sandy loam which is brownish yellow (10YR 6/6) when dry; weak fine granular structure; loose when moist and slightly hard when dry; threads and cores of very pale brown (10YR 8/4) fine sand occur in the many former root channels; strongly acid.
B_{1b}	10-16	Strong brown (7.5YR 5/6) fine sandy loam which is reddish yellow (7.5YR 6/6) when dry; moderate fine granular structure; very friable when moist and slightly hard when dry; strongly acid.
B_{2b}	16-34	Yellowish-red (5YR 4/8) fine sandy clay loam which is yellowish red (5YR 5/8) when dry; moderate coarse and medium subangular blocky structure; friable when moist and hard when dry; strongly acid.
B_{3b}	34-58	Yellowish-red (5YR 5/8) fine sandy loam which is reddish yellow (5 YR 6/8) when dry; weak fine granular structure; loose when moist; very strongly acid.
C_b	58-144	Thinly stratified beds of yellowish-red (5YR 5/8) and very pale brown (10YR 7/4) loose fine sand; essentially structureless and single grained; very strongly acid.

The morphology of the buried profile is essentially the same as that of Ruston fine sandy loam, described in detail recently by Templin, Martin, and Dyal (1951, p. 480-481), except for the absence of a thin but distinct A_1 horizon. The sequence, thickness, color, structure, texture, and consistence of the horizons are all like those of Ruston fine sandy loam. Furthermore, the Coastal Plain sediments immediately beneath the loess in the section described by Wascher, Humbert, and Cady (1947, p. 391) in Obion County, Tennessee, comprise the solum of an almost identical buried soil. In that buried soil, the A_b horizon is a yellowish-brown (10YR 5/6) sandy loam containing 16.4 percent clay and the B_b horizon a mixed yellowish-red (5YR 5/8) and red (10R 4/6) sandy clay loam containing 29.6 percent of clay. Sand

[9] Grateful acknowledgment is extended to Irving L. Martin who prepared the diagram of the exposure and the detailed description of the buried soil profile.

contents in both horizons slightly exceed 50 percent. Similarities between the buried profiles described in Carroll County, Mississippi, and Obion County, Tennessee, and the modern Red-Yellow Podzolic soils in the southeastern United States are greater than those between buried and modern Gray-Brown Podzolic soils in the Upper Mississippi Valley.

Red-Yellow Podzolic soils comprise a group with very thin dark A_1 horizons over leached, light-colored A_2 horizons underlain by red, yellowish-red, or yellow finer-textured B horizons that grade into lighter-colored, often reticulately mottled C horizons. These soils have been formed from a variety of rocks, mainly siliceous, under forest vegetation that was coniferous, deciduous, broadleaf evergreen, or mixed in composition. Dominant well-drained soils of the southeastern United States, the Red-Yellow Podzolic group occurs characteristically in humid, warm-temperate climates but extends into the tropics as well. Horizon differentiation in Red-Yellow Podzolic soils is due mainly to reduced amounts of silicate clay minerals and sesquioxides in the A horizon and increases in those constituents in the B horizon. On the whole, Red-Yellow Podzolic soils are more strongly leached and weathered than Gray-Brown Podzolic soils, with which they merge along their cooler boundary. The members of the Red-Yellow Podzolic group with reddish B horizons are marked by stronger chromas and redder hues in the B horizons reflecting the greater release and accumulation of iron oxides.

Buried Red-Yellow Podzolic soils, identical in gross morphology with the ones in Carroll County, Mississippi, and Obion County, Tennessee, are common in the loess belt east of the Mississippi River. Exposures of such profiles have been observed by the author in a large number of places in Mississippi, Kentucky, and Tennessee. In addition to buried "Ruston" soils from moderately sandy sediments, there are also buried profiles from fine-textured marine sediments. At one end of the exposure in Carroll County, Mississippi, the sandy sediments are replaced by clays. Formed from the clays is a Red-Yellow Podzolic profile similar in general appearance and sequence of horizons to the Boswell series, also described by Templin, Martin, and Dyal (1951, p. 478-479). The Boswell series, widely distributed from Texas to Georgia, is a member of the Red-Yellow Podzolic group formed from fine-textured marine clays.

A buried soil from marine sediments intermediate in texture between those giving rise to Ruston and Boswell soils occurs 2.5 miles east of the Tennessee River in a cut along U. S. Highway 68, Trigg County, Kentucky. This buried soil is covered by 5 feet of loess within which a profile of Grenada silt loam has been formed. The A_b horizon of the buried soil is like that of the buried "Ruston" profile in Mississippi, but the B_b horizon is somewhat finer textured and slightly redder in color. The buried profile closely resembles the Luverne series, a Red-Yellow Podzolic soil from marine sediments of moderately fine texture in Mississippi, Alabama, and Louisiana.

Buried Red-Yellow Podzolic soils from loess and sandstone.—Some additional notes on buried profiles will illustrate the variety of geological materials from which they have been formed. Because these profiles are all Red-Yellow Podzolic soils, detailed descriptions are not given.

Several buried profiles from the "third" loess[10] described by Wascher, Humbert, and Cady (1947, p. 391-392) are considered by the author to be Red-Yellow Podzolic soils. The buried profiles from the "third" loess in the sections in Obion and Dyer Counties, Tennessee, and in Tallahatchie County, Mississippi (Wascher, Humbert, and Cady, 1947, p. 380-392), have the same kinds and sequence of horizons as the buried "Ruston" soil in Carroll County, Mississippi. The A_b horizon is a light brown (7.5YR 6/4) silt loam and the B_b horizon a yellowish red (5YR 5/8) to strong brown (7.5YR 5/8) silty clay loam in the soil from the "third" loess in the Obion County section. The buried soils from loess are more silty than the ones from marine sediments, but otherwise the profiles seem to be alike. In addition, the clay minerals of the buried soils from the "third" loess are comparable to those common in the more weathered Red-Yellow Podzolic soils (Dyal, Martin, and Templin, 1951, p. 485-487).

Now covered by 4 feet of loess, a buried soil profile from sandstone is exposed in a cut along U. S. Highway 41 approximately 0.1 mile north of its junction with U. S. Highway 61 in Hopkins County, Kentucky. The A_b horizon of the buried soil from sandstone is less distinct than that of the buried "Ruston" soil in Carroll County, Mississippi, but the B_b horizon of strong brown (7.5YR 5/8) sandy clay loam is equally prominent. Except for the presence of small sandstone fragments, it could pass for the B horizon of Ruston fine sandy loam. The buried soil from sandstone is comparable to the Linker series, occurring widely but of limited extent in northern Alabama, northern Arkansas, and eastern Kentucky.

Genesis of Red-Yellow Podzolic soils.—The high degree of similarity in morphology and the apparent similarities in clay contents, clay distribution, kinds of clay minerals, and cation exchange capacities between the buried and modern Red-Yellow Podzolic soils raise interesting questions about the origin of the modern soils. On the basis of the similarities, Thorp Johnson, and Reed (1951, p. 10-11) suggest that Red Podzolic soils with prominent horizons are relict soils, possibly formed during Yarmouth time. At least, they consider those soils to be polygenetic in the sense of having evolved under two or more climatic regimes.

Whether the modern Red-Yellow Podzolic soils are relicts of a former geologic period cannot yet be established, but it should be one of the working hypotheses in considering their possible genesis. Beyond that, it seems highly probable that they are polygenetic. In fact, as the study of soil genesis continues, more and more soils are found bearing the marks of more than one cycle of horizon differentiation, though the marks may be prominent in some cases and obscure in others. More quantitative data on the buried zonal soils of the lower Mississippi Valley will be needed for rigorous comparison of the buried profiles with their analogues on the land surface to the east and west. Full discussion of the genesis of Red-Yellow Podzolic soils does not seem appropriate here, but it does seem desirable to call attention to the significance of the buried profiles in understanding soil formation.

[10] Possible correlation as Loveland loess is suggested by Wascher, Humbert, and Cady (1947, p. 390) and supported by Leighton and Willman (1950, p. 616).

LOESS AND BURIED SOILS, LOWER MISSISSIPPI VALLEY

The nature and distribution of buried soil profiles beneath the loess deposits of the lower Mississippi Valley throw an interesting sidelight on the origin of those deposits. Leighton and Willman (1950, p. 613-622) reviewed theories of origin of loess sheets in the Mississippi Valley, considered the supporting evidence, and concluded that the loess was laid down by wind. This view has wide but not universal acceptance. Recently, Fisk (1951) has offered further argument for the theory of loess origin proposed by Russell (1944). According to this theory, the loess was formed from sediments similar to present back-swamp clays of the Mississippi River, in part by aggregation of clay particles into silt particles and in part by the sorting and concentration of silt particles through downslope creep. The widespread occurrence of buried soils beneath the loess, soils with morphological features that reflect good drainage and aeration, seems to bear directly on this theory of loess origin.

The buried Red-Yellow Podzolic soils which underlie the loess from Kentucky to Louisiana are identical in morphology with the Red-Yellow Podzolic soils on the present land surface, both east and west of the loess belt. Modern Red-Yellow Podzolic soils do not exist where drainage and aeration are poor. They occupy undulating to rolling topography, whereas other great soil groups are found in depressed positions. This can be observed at numerous places in the Gulf Coastal Plain by following changes in soil profiles from a convex upland ridge downslope into concave or depressed sites. This is often possible within a distance of 100 yards.

Further evidence of the importance of good aeration and drainage to persistence of bright B horizon colors of Red-Yellow Podzolic soils is offered by changes which have followed waterlogging. Near the margins of the reservoirs in the Tennessee Valley, some soils are flooded intermittently. These are usually wet for a few weeks each year. In such areas, profiles of Fullerton silt loam, a Red-Yellow Podzolic soil from moderately cherty limestone are affected within a decade by the intermittent flooding. The original red to yellowish-red colors of the B horizon have been dulled, and gray and yellow mottles have appeared in ten years. During this short interval of time, these Fullerton profiles have taken on the appearance of soils commonly transitional between the Red-Yellow Podzolic and the associated wet great soil groups, such as Low Humic-Gley soils. Similar observations have been made in an area of Red-Yellow Podzolic soils diked for paddies on Okinawa. These paddies were flooded for approximately 6 weeks at the beginning of each crop season, after which the water supply was exhausted. Soils examined by the author after they had been paddies four years had already lost the uniform red color of the B horizon. The mottled pattern of colors included yellow, yellowish red, and light gray. Distribution of the paddies among non-irrigated fields of well-drained Red-Yellow Podzolic soils seemed conclusive evidence that the whole area was uniform five years earlier. As periodic flooding continues, the changes in color will also continue. Soils that were originally of the Red-Yellow Podzolic group have been used for rice paddy culture in Japan for centuries. Inside the paddies, the soils are now of the Planosol or Low Humic-

Gley group, sometimes uniformly gray in color and sometimes dominantly gray with mottles of yellow and yellowish brown. Outside the paddy boundaries and everywhere among them are typical Red-Yellow Podzolic soils, indicating the original character of soils in that area.

The association of B horizon colors of Red-Yellow Podzolic soils with good aeration and drainage seems to prevail without exception. Moreover, observations in Tennessee and Okinawa demonstrate that the colors are easily altered when changes in moisture regime introduce reducing conditions. It seems impossible that the buried Red-Yellow Podzolic soils beneath the loess of the lower Mississippi Valley were wet at any stage in their history. The rapidity with which changes in color can occur argues strongly against waterlogging of the soils at any time. Because Red-Yellow Podzolic soil profiles are so widespread beneath the loess, it seems clear that the former land surface was generally well drained, perhaps better drained than the present one. Thus, the buried soils seem an insurmountable obstacle to the theory of loess origin proposed by Russell (1944), especially when this evidence is combined with observations of the current soils in backwater areas of the Mississippi River flood plain. Red-Yellow Podzolic soils are completely lacking from such areas, which are occupied by Humic-Gley and Low Humic-Gley soils showing clear signs of reducing conditions. The nature of the buried soils beneath the loess of the lower Mississippi Valley seems to preclude deposition of that loess by any other means than by wind.

RELATIONSHIPS AMONG BURIED SOILS IN MISSISSIPPI VALLEY

Discussion is restricted to buried zonal soils because they have been described in some detail in both the upper and lower parts of the Mississippi Valley. Furthermore, studies of zonal soils shed more light on possible past climates and vegetation, within our present understanding of soil genesis. Present examination of the similarities and differences among the buried zonal soils is of interest, although more useful comparisons will be possible when the nature and properties of buried soils are better known. For example, it would be of special interest to have careful comparative studies of the buried soil profiles formed from Loveland loess in western Iowa and the analogous profiles from the "third" or Loveland loess in western Tennessee.

Morphologically, the buried Gray-Brown Podzolic soils of the upper Mississippi Valley are a trifle more like the buried Red-Yellow Podzolic soils of the lower Valley than are their modern counterparts. This slightly greater similarity is in color of the B_b horizons. In the buried Gray-Brown Podzolic soils, the B_b horizons are a little redder and seem to have stronger chromas than do the B_b horizons of the modern representatives of the group. Colors of the B_b horizons range from yellowish brown (10YR 5/4) to strong brown (7.5YR 5/6), whereas colors as red as strong brown have not been found in the B_2 horizons of Gray-Brown Podzolic soils from Wisconsin loess in Iowa (Scholtes, Ruhe, and Riecken, 1951, p. 305-306). In the buried Red-Yellow Podzolic soils, the colors of B_b horizons range from strong brown (7.5YR 5/6) to red (2.5YR 5/8), with most of them falling near yellowish red (5.YR 5/6-5/8). Thus, the colors of B_b horizons of buried Gray-Brown Podzolic

soils overlap those of the comparable horizons of buried Red-Yellow Podzolic soils. Furthermore, the modal color for the B_h horizons of the buried Gray-Brown Podzolic soils seems to be nearer the strong brown (7.5YR 5/6) than the yellowish-brown (10YR 5/4) end of the range. Thus, with respect to color of the B_h horizon, the buried Gray-Brown Podzolic soils seem to grade toward the Red-Yellow Podzolic groups. Possible significance of this is discussed above.

Except for the smaller differences in colors of B_h horizons, the buried Gray-Brown Podzolic and Red-Yellow Podzolic soils seem to be no more alike than are modern representatives of the two groups. Distribution and overlap in the clay contents, clay distribution curves, types of clay minerals, and cation exchange capacities seem to be about the same for the buried and modern zonal soils. Clay distribution, kinds of clay minerals, and exchange capacities seem to cover the same ranges in buried Red-Yellow Podzolic soils as they do in those now on the land surface. For the buried Gray-Brown Podzolic soils, the maximum clay contents in the profiles seem to be toward the high end of the range found among modern representatives. In this one respect, the buried Gray-Brown Podzolic and Red-Yellow Podzolic soils seem to differ a trifle more than do the modern soils. Field observations made by the author, over and above those reported in this paper, indicate that the distinctions among the buried soils, on the one hand, and the modern soils, on the other, are of the same order of magnitude.

PERSISTENCE OF HORIZONS IN BURIED SOILS

Whether soils are preserved when covered by more recent sediments depends upon the kinds of horizons in the profile, the degree of horizon differentiation, and the processes responsible for burial. The kind of horizons and the change in environment that brought on a new cycle of sedimentation seem more important than the degree of horizon differentation. Faint horizons are less likely to persist than prominent ones, other things being equal.

The formation of horizons in soil profiles is due to one or more of the following: Accumulation of organic matter, gains or losses in silicate clay minerals, gains or losses in sesquioxides, changes in color (usually accompanying other changes), cementation, and development of characteristic structure. Horizons due to accumulation of organic matter persist under some circumstances, but they are less stable, for example, than horizons due to gains or losses in silicate clay minerals. The distribution curves for silicate clay minerals, as well as those for sesquioxides, are persistent features which can be expected to last for a long time. Cemented horizons may persist indefinitely, as is evident from the occurrences of laterite in parts of Australia (Stephens, 1946, p. 7-15). The characteristic structure of some horizons also seems to persist for long intervals, as indicated by the subangular blocky structure of the B_{2h} horizons of the Yarmouth Gray-Brown Podzolic soil in Iowa and the buried Red-Yellow Podzolic soil in Mississippi. The probable persistence of different kinds of horizons under conditions in the given locality should always be considered carefully in the study of buried soil profiles.

The changes in environment which immediately precede or accompany a new cycle of sedimentation may also determine how well soil profiles are preserved. An advancing glacier may completely destroy a soil profile on the land surface over which it is advancing, either mechanically by its own action or through frost-churning or solifluction beyond its margins. As a general rule, soils were strongly disturbed by the successive glaciers in the upper Mississippi Valley, and a period of active erosion seems to have immediately preceded deposition of the Wisconsin loess in southern Iowa. Buried soil profiles are lacking at the loess-till contact in a number of exposures, yet they occur in many others. An advancing lava flow may change the soil, at least in the uppermost inches of the profile, because of the intense heat. A brown to reddish-brown layer about 3 inches thick was noted by the author in weathered materials immediately beneath dark basalt in the Deccan plateau near Betul, India. This thin layer was interpreted as one effect of the hot overriding lava flow which crystalized into the basalt. Deposition of sediments by water may or may not be accompanied by prolonged waterlogging of soils on the former land surface. Sandy alluvium may be laid down to considerable thickness in a few days, whereas the settling of clays takes far longer. With buried soils reported under loess, glacial drift, volcanic ash, alluvium, and lava flows (Norton, 1930; Schonhals, 1950; Schultz, Lueninghoener and Frankforter, 1951, p. 28-33; Simonson, 1941; Thorp, Johnson, and Reed, 1951; Wascher, Humbert, and Cady, 1947, p. 390-392), there must have been abundant opportunity for changes in soils as former land surfaces were being covered by new sediments. The possibilities of change in an existing soil profile as it is being buried must always be considered in the study of buried soils.

As a general rule, careful examination of a number of exposures will be required before it becomes clear that the observed features are parts of buried profiles. Careful study of several exposures may suggest that part of a soil profile or parts of more than one profile are present, though the sequence of horizons may not be complete enough for identification. The profile may also have been much changed during the new cycle of sedimentation. Difficulties of this kind compound the problems of identification and interpretation of buried soils, troublesome at best because of limited knowledge of soil genesis. Wherever buried soils can be identified with reasonable assurance, however, their study and careful interpretation should become increasingly useful in Pleistocene geology.

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SILICIFICATION OF ROCKS BY SURFACE WATERS

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ABSTRACT. Surface silicification of rocks is of widespread occurrence in Tanganyika. It is very general in the case of ultrabasic rocks but is shown by many other rocks and minerals. The causes of this phenomenon are considered with reference to a striking example on the Sagara escarpment. Weathering of basic rocks leads to the formation of siliceous alkaline solutions which, travelling downhill, soak into any porous material in their path, including weathered rock of the same nature as that from which they have been derived. Silica is slowly deposited, silicifying rocks or minerals of many kinds. Jaspers result from silicification of the clay-like insoluble residues of rock weathering. Silica still left in solution after these processes is carried into mbugas, lakes and rivers and is there deposited along with calcium and magnesium carbonates; it is a main source of the high silica content of mbuga and lake limestones.

SILICIFICATION OF ROCKS BY SURFACE WATERS

At various times during the past few years, rocks which have been undergoing silicification by mainly amorphous silica have been sent into the Geological Survey of Tanganyika for examination. Such rocks have come from widely separated localities and had frequently been ultrabasic or at least basic before silicification. Some jasper-like materials had been sent from the same localities.

These silicified materials raised three important questions:

(1) Why should ultrabasic rocks be especially prone to such silicification?

(2) What is the nature and origin of the jasper-like material?

(3) In what manner does the silicification take place?

It is possible that the answer to these questions would not be the same in all cases, but a recent opportunity to examine an area of silicification has provided the answers which it is thought apply to the great majority.

In June 1953 Mr. Ayton brought in some wad from the Sagara escarpment and in September some silicified wad from the same locality. In October I visited the locality with Mr. Ayton. It is approximately 3 miles east of the Sagara Spring, approx.: 6° 15′,; 36° 33′ E and about 800 feet above it, and is reached by a cattle track. At this height the hills are covered by miombo forest and the rainfall is evidently sufficient to cause active weathering of the rocks. Some weathered aplite looked almost like weathered limestone. The cattle track followed a band of hard quartzose gneiss. Parallel to this and about 75 feet higher up the hillside ran a band of basic rocks full of ferromagnesian minerals. This rock had been completely rotted by weathering and all the rocks lower down the grassy slope were silicified in places though unsilicified areas or patches could also be found. In some places there was quite friable wad; in other places it had been converted into a black splintery rock too hard to scratch with a knife which could still liberate chlorine from concentrated hydrochloric acid. A pyritic outcrop that had been largely oxidized to "gossan" had, much of it, been silicified to a type of jasper. Most interesting of all, however, was the material washed down the hillside into a slight depression. In two different places shallow pits had been sunk in

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this. It consisted of soft material, some of it sulphur yellow in color, essentially a talc-kaolin mixture stained by a little iron; some brownish yellow and some red, consisting essentially of more or less hydrated ferric oxide. Here and there in this soft material were hard lumps of "jasper" of the same yellow, brownish or red color as the surrounding soft material. This was highly silicified, broke easily with a conchoidal fracture, and was very brittle. The wad and these earthy materials, being porous, had been permeated by the siliceous waters and converted into compact hard silicified rock. Non-porous material in the same general area, such as crystals of tremolite and other mineral and rock fragments, had become covered and often cemented together by opaline silica.

The explanation of these facts is as follows: The normal process of tropical weathering removes alkalis and silica in aqueous solution. Calcium is removed either as soluble bicarbonate or, where the rocks contain small amounts of pyrites, as the fairly soluble gypsum. Some magnesia is also removed as bicarbonate. The rest of the magnesia tends to form talc and the alumina kaolin or pyrophyllite, while iron forms ferric hydroxide or oxide. Under certain conditions aluminum yields aluminum hydroxide, the chief constituent of bauxite, though this is either very rare or does not happen in Tanganyika. Some of the insoluble residues of the weathering process get washed down the hillsides and collect in favorable places as clay-like deposits. The alkaline siliceous waters running or seeping downhill saturate any porous material, and in these silica is slowly deposited, so that the material is silicified. The materials that become silicified in this way can be:

(a) Part of the same partially weathered rock as that which supplied the silicifying solution. At lower levels, where the rock has become porous as a result of weathering, it becomes impregnated and slowly silicified by the solutions derived from higher levels of the same rock.

(b) Any other porous material in the path of the siliceous waters, including the settled out deposits formed by the insoluble products of weathering.

(c) Non-porous material may become covered with a film or even a thick coat of amorphous silica which may cement together loose rubble and produce a solid rock.

The reason why ultrabasic rocks are particularly liable to become silicified is that they are decomposed and become porous, as a result of weathering, far more readily than most other rocks. Silicification of the type described is of widespread occurrence in Tanganyika and has no connection, as is sometimes suggested, with the waters from hot springs. Though most pronounced in areas where there are many basic rocks, some of its effects can be seen even in areas composed essentially of granitic rocks. Thus the whitish streaks which are often seen on vertical faces of granite or migmatite are commonly due to gypsum which has been hardened and rendered less soluble by silica either deposited at the same time or subsequently.

The silica in the surface waters which is not accounted for by the above described silicification process finally finds its way into mbugas, lakes or

rivers. There it becomes co-precipitated with calcium and magnesium carbonates and is one of the chief sources of the high silica content of mbuga and lake limestones. In the mbuga limestones it is normally disseminated as finely divided amorphous silica. In Pleistocene lake deposits the silica has usually become concentrated into bands and nodules of amorphous opaline silica. The surface limestones formed by deposition on the hill slopes also frequently contain bands of amorphous silica as a result of deposition of a coating of amorphous silica over the relatively non-porous limestone.

Geological Survey of Tanganyika
Dodoma

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DETERMINATION OF THE RADIOACTIVITY OF THE QUINCY GRANITE BY THE PHOTOGRAPHIC METHOD

Mme. A. HEE, R. P. DERVILLE, and M. JAROVOY*

ABSTRACT. Approximate uranium and thorium contents of powdered Quincy (Mass.) granite have been determined with nuclear photographic emulsions. Compared with previous results, obtained by different methods, the new values have a wide range, because the radioactive elements are concentrated in distinct centers scattered haphazardly through the rock. The radioactive centers have been localized in thin sections by the emulsion techniques; they are found chiefly in sphene and ilmenite associated with riebeckite. The nuclear emulsion technique, which delineates the distribution of radioactive atoms in various accessory minerals may be useful in the study of the problem of geologic age of rocks.

INTRODUCTION

The Quincy granite has been studied by many workers, and the concentrations of radium, uranium, thorium, potassium and helium are given in various publications, particularly in the important work of Evans and Goodman (1941) on the radioactivity of rocks and in an article by Keevil (1938). Keevil's average values for the whole rock are given below:

Ra x 10^{12}	U x 10^6	Th x 10^6	He x 10^5	Th/U	K x 10^2
g/g	g/g	g/g	cm^3/g		g/g
0.98	2.78	12.4	4.33	4.5	3.8

The potassium concentration was also given in an article by Hess (1947). This value agrees with that reported in a chemical analysis of the Quincy granite quoted by Osann (1916).

DETERMINATION OF URANIUM AND THORIUM CONCENTRATIONS IN POWDERED SAMPLES OF THE QUINCY GRANITE BY A PHOTOGRAPHIC METHOD

During the beginnings of our work on the photographic method applied to the study of uranium and thorium concentrations in powdered rock by the technique given by Madame Joliot-Curie (1946) and by Yagoda (1949) it seemed interesting to us to compare our results to those found by older and entirely different methods. The Quincy granite was ideally suited for this purpose. Professor P. M. Hurley of the Massachusetts Institute of Technology has kindly sent us a sample of this rock, for which we are deeply grateful.

Of our various analyses we list only those of two separate powdered samples:

	U x 10^6 g/g	Th x 10^6 g/g	Th/U	Ra x 10^{12} g/g
Powder 1 plate no. 311	5.1	18.7	3.7	1.7
Powder 2 plate no. 325	2.1	10.4	4.9	0.7

We believe the differences found in the concentrations of the elements are not due to experimental errors. One can see that the thorium-uranium ratio varies only within acceptable limits, but the concentrations of uranium and thorium vary simultaneously by almost a factor of two.

The study of the localization of radioactive centers of which we shall speak later leads us to believe that the differences in concentration are due

*We are indebted to H. Faul for this translation of our paper.

to the irregular distribution of radioactive centers in a mass whose radioactivity is low in comparison. According to our study the active surface is only 1.6 percent of the total surface. We shall see that the atoms of uranium and thorium are contained in very small crystals, the distribution of which is certainly far from homogeneous, so that we should not be surprised at the diversity of results obtained on different powdered samples.

Keevil (1938) gives the results of measurements on eight different samples of Quincy granite. These results show great variation as follows: 2.75 to 5.31 x 10^{-5} cm^3/g for helium, 0.77 to 1.28 x 10^{-12} g/g for radium, 5.9 to 12.4 x 10^{-6} g/g for thorium.

It is true that the same author (Keevil et al., 1943) later attempted to establish a law of distribution of radioactivity in batholiths. He observes a tendency for the radioactivity to decrease from the border toward the center. However, speaking of the granodiorite massif of Bourlamarque, he adds that the variation along a profile does not proceed gradually from specimen to specimen. Actually, two high values found near the center were due to an abnormally strong local concentration of zircon.

The relation between the radioactivity and the presence of certain accessory minerals cannot be escaped. We can hardly hope to find a perfect agreement between different specimens of a granite considering the fact that the crystals which contain the radiaoctive elements are irregularly distributed in the rock. One need only consider the extremely small size of the radioactive centers and their haphazard distribution in the relatively inert mass of the rock.

In the evaluation of the concentration of uranium and thorium in powdered samples of the Quincy granite we have considered the background of the Ilford plates. We have previously called attention to the importance of this factor (Hée et al., 1951). The background was determined by running a blank plate. In this case the background amounts to 30 to 40 percent of the measured radioactivity of the powders. This correction is of the same order of magnitude as that of the leakage current of a quadrant electrometer with which one measures the weak ionization currents due to the radioactivity of such rocks.

LOCALIZATION OF RADIOACTIVE CENTERS IN THE QUINCY GRANITE

We have used first the shadowing method previously described by one of us (Hée, 1948) for the study of opaque parts of petrographic thin sections. Afterward, the photographic emulsion (Ilford C2) was poured directly on the uncovered thin sections, following the suggestion of Ford (1951). This procedure is rapid and the precision of localizing radioactive centers in the transparent areas is perfect. In the opaque areas the tracks can be discerned along the borders, but it is prudent to study the thin section according to the shadowing method (Hée, 1948) as well, before covering it with a photographic emulsion.

Unfortunately, the presence of the photographic emulsion on the thin section adds to the difficulties of mineralogic determination of the radioactive centers, which frequently are extremely small. Nevertheless, with some ex-

perience, a good mineralogist becomes used to viewing the rock through the additional layer of photographic emulsion. Where it is absolutely impossible to recognize the minerals through the emulsion, one can carefully remove the emulsion after meticulously fixing the position of the radioactive centers. This orientation is fairly easy in the granite because of the very definite outlines of grains of major minerals. Wherever necessary, one can refer to photomicrographs made before the emulsion was removed.

Two thin sections were studied, numbers 36 and 28. The first was investigated over part of its surface and the second over its entire surface. The latter was, furthermore, especially examined from the point of view of possible contamination. Our emulsion was poured directly onto the section, thus minimizing the background. Table 1 shows the distribution of alpha tracks in these thin sections. In the various columns we have shown the following data:

Column 1. Exposure time.

Column 2. The number of important radioactive centers found on the examined area S of the thin section.

Column 3. The number of alpha particles emitted by the centers on each slide.

Column 4. The approximate surface S_c occupied by these centers.

Column 5. The examined area S of the thin section.

Column 6. The number of tracks on the area $S\text{-}S_c$.

Column 7. The average number of alpha tracks per centimeter square of $S\text{-}S_c$.

Column 8. The average number of tracks per centimeter square of the emulsion area exposed only to the glass backing of the thin section.

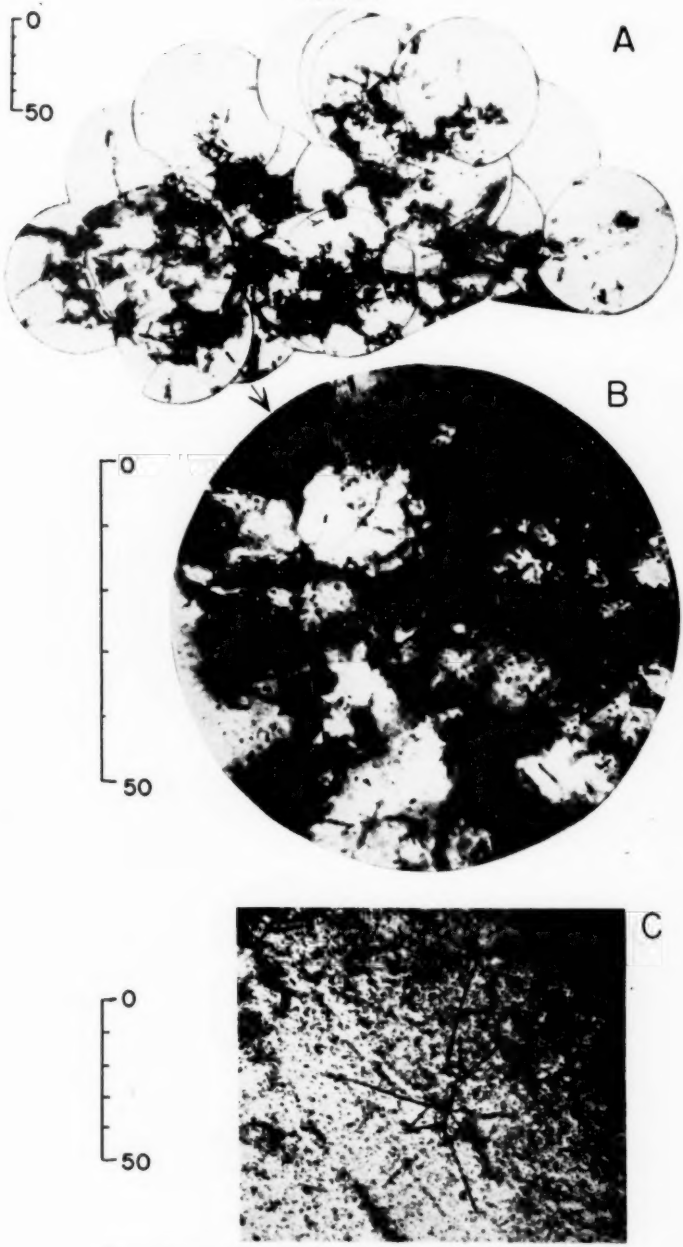
Column 9. The average number of tracks per square centimeter of emulsion on a blank slide.

TABLE 1

	1		2	3	4	5	6	7	8	9
	Days	Hours			S_c mm²	S mm²				
Number 28 Emulsion 396	25	21	53	877	2.89	189	449	241	139	
Number 36 Emulsion 503	19	17	9	409	1.065	186				
Blank Emulsion 340	13	0								98

If we admit a proportional relation between the number of background tracks and the time of exposure it becomes clear that the edges of section 28 are not particularly contaminated. The number of tracks seen in this part corresponds to the background on the blank. Furthermore, the number of tracks per square centimeter of surface $S\text{-}S_c$ is 241 minus 139 equals 102, or of the order of magnitude one would expect from the radioactivity of the glass and the emulsion itself. Area $S\text{-}S_c$ is occupied by feldspar, quartz, and ferromagnesian minerals. If we consider the ratio of the number of disintegrating atoms per unit area of the active centers to the number of disintegrating atoms per unit area of the other parts of the section, we find

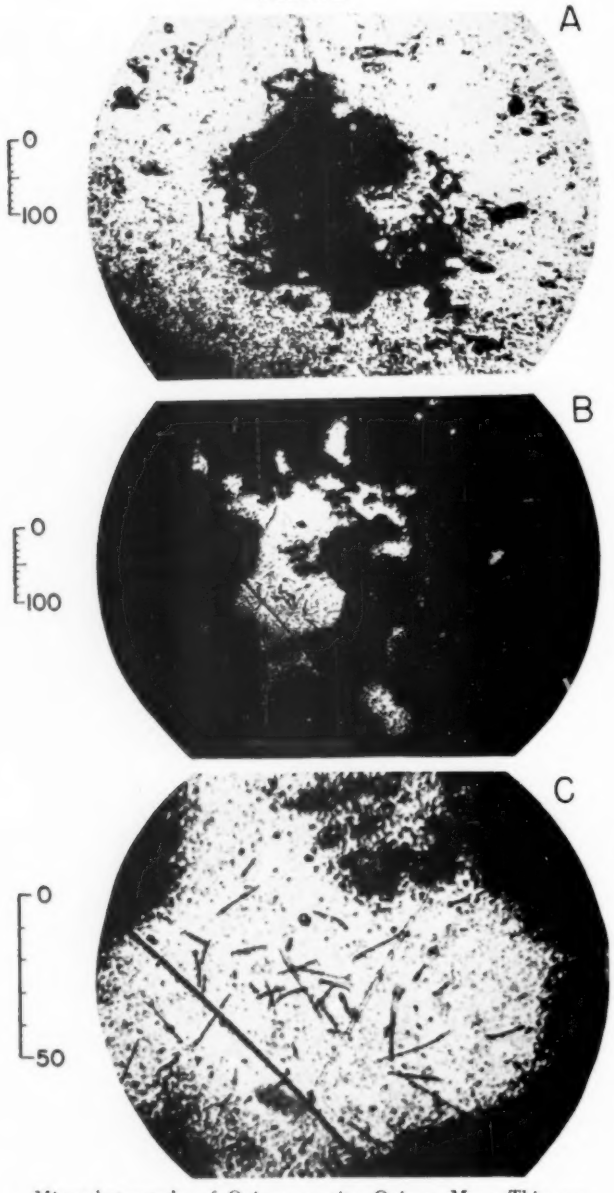
PLATE 1



Microphotographs of Quincy granite, Quincy, Mass.
Thin section 28, emulsion 396. Scales are in microns.

A. Center 4, large crystal of sphene.
B. Part of center 4, enlarged, showing α-particle tracks.
C. Center 149, small crystal of sphene?, showing radiating α-particle tracks.

PLATE 2



Microphotographs of Quincy granite, Quincy, Mass. Thin section 28, emulsion 371, center 67, ilmenite. Scales are in microns.
A. Positive print of thin section.
B. Ilford plate with α-particle tracks.
C. Part of same enlarged.

30,300/102 or about 300. This ratio shows how highly centralized in extremely small areas the radioactive atoms are, with the exception of certain parts of biotite near radioactive centers which seem to show an activity slightly higher than the background.

Picciotto (1950) in his study of the granite of Blanc Lake in the Vosges Mountains, Coppens (1950) in his study of the radioactivity of rocks, and ourselves (Hée, 1948, 1951) have already mentioned this segregation of radioactive atoms in rocks. Larsen and Keevil (1942) in their study of gravity separates of constituent minerals, have shown that in the Lakeview tonalite, Riverside County, California radioactive elements are concentrated in apatite, zircon and sphene.

SUMMARY OF THE PRINCIPAL RADIOACTIVE CENTERS FOUND IN TWO THIN SECTIONS OF THE QUINCY GRANITE

All the alpha tracks were measured with the aid of a microscope. The point of emission on the surface of the thin section is marked by a number. Table 2 lists the principal radioactive centers with their approximate dimensions, the number of alpha tracks, and the mineralogic identification of the centers. The exposure time is shown in table 1.

In summary, the active centers are found in sphene and in ilmenite located in the immediate vicinity of or even within riebeckite. The last mineral itself shows alpha tracks only rarely. The roughly estimated length of the tracks (without the establishment of histograms) shows that we are dealing with atoms that belong to the uranium and thorium families.

We should add that in both of these thin sections we have found only a single radioactive center which corresponds to a well-developed crystal. The crystal is brown, deeply colored, birefringent, and strongly pleochroic in dark brown and black, alpha equals zero. The strong natural coloring does not permit estimating the birefringence hues nor the sign of elongation. The mineralogic determination could not be made exactly, but we are dealing with a mineral similar to rutile of the variety nigrine, ilmeno-rutile, a colored variety of sphene (titanite), or allanite. This center does not appear in the list given in table 2 because it occurs in a region of thin section no. 36 which was not methodically investigated.

REMARKS ON THE MAGNETIC PROPERTIES OF THE QUINCY GRANITE

The chemical analysis given by Osann (1916) shows the presence of titanium which we find in sphene and in ilmenite. We have again shown what we had already mentioned (Hée et al., 1951); namely, that a rock of relatively moderate susceptibility does not necessarily contain magnetite but more likely ilmenite as the paramagnetic material. The susceptibility of the Quincy granite is of the order of 36×10^{-6}, analogous to that of the Raon-l'Etape granite in the Vosges Mountains (25×10^{-6}).

TABLE 2

Section	Number of Center	Dimensions μ	Number of Alpha Tracks	Mineralogic Identification
Number 28 Emulsion 396	1	100 x 100	16	Sphene
	4	300 x 200	100	Sphene in colored and highly birefringent grains, leaving the possibility that it may be a different mineral (see pl. 1-A and B).
	9	100 x 100	6	Sphene?
	14	300 x 300	7	Sphene and riebeckite
	16	200 x 200	9	Intergrowth of sphene, riebeckite, and ilmenite?
	67	1000 x 1000	150	Ilmenite?, opaque mass with clear and ilmenite?
	73	80 x 150	7	Sphene, ilmenite
	121	50 x 70	7	Sphene, ilmenite
	135	100 x 100	35	Three grains which are similar to number 4 and are difficult to identify because of the surrounding riebeckite.
	147	50 x 20	7	Sphene in riebeckite
	149	35 x 15	10	Sphene? See pl. 1-C.
	152	10 x 10	9	Sphene
	155	80 x 60	22	Sphene in riebeckite
	180	150 x 100	>100	Opaque mass like number 67, ilmenite?
	196	450 x 250	107	Sphene? Masked by a rust-colored mineral (limonite)
	240	50 x 50	11	Sphene
	250	15 x 15	12	Sphene
	258	100 x 20	20	Sphene?
	278		35	Ilmenite
	283	50 x 50	16	Sphene, riebeckite, ilmenite
Number 36 Emulsion 503	17	500 x 500	8	Sphene, locally sprinkled with ilmenite and all in a riebeckite crystal.
	25	200 x 40	12	Sphene, ilmenite
	27	100 x 80	27	Sphene
	52	200 x 150	25	Riebeckite according to the birefringent colors, masked by an undetermined mineral.
	60	650 x 200	38	Intergrowth of sphene, ilmenite, and riebeckite
	64	150 x 70 120 x 100 150 x 100 30 x 50	300	Four sphenes

COMPARISON WITH N. B. KEEVIL'S RESULTS ON THE QUINCY GRANITE

As we have already mentioned above, the work of Keevil showed about 10 years ago that radioactive atoms tend to be concentrated in certain accessory minerals. The photographic method confirms these early results as far as granites in general are concerned. The radioactive concentrations are found in zircon, sphene, magnetite, ilmenite, and apatite. However, Keevil et al. (1943) report mineralogic studies of two specimens of Quincy granite where they mention minerals which we have not encountered in our thin sections, for example, epidote, zircon, and needles of apatite. Like ourselves they mention the presence of numerous sphenes, but they have not been able to establish a direct relation between the presence of sphenes and total radioactivity in the Quincy granite. We are in disagreement on this point and we find it difficult to explain this divergence of opinion. The results of these early American researches are on the whole very precise, and the photographic method confirms them in all other respects.

CONCLUSIONS

The photographic study of powdered samples of Quincy granite has led to two principal results:

(1) The variations in uranium and thorium concentration found in photographic studies of powdered rocks are about the same as those one obtains by other methods. The study of the length and number of alpha tracks in photographic emulsion is laborious. However, this work is less difficult than the various operations required for the determination of radon and thoron by the classic methods. The apparatus described by Evans and Goodman (1941) appears to be the only one that is more rapid. Whatever method one uses, the determination of concentration of uranium and thorium in the total mass of a rock cannot be made with any reasonable accuracy. The indubitable establishment of this fact by the photographic method may lead to a new approach to the interpretation of helium age determinations on rocks.

(2) The photographic method is perfectly suited to the study of radioactive centers in rocks, particularly when one uses emulsions that have been deposited directly on the thin section and/or on the microscopic crystals which contain radioactive atoms. The small radioactive minerals can be separated from the large mass of relatively inactive material. In our current work we are proceeding in this general direction.

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SCALE MODEL REPRODUCTION OF TENSION FAULTS

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ABSTRACT. Normal or tension faults were produced in the laboratory and simulate those observed in basin and range structural regions. Apparatus was designed with due regard for scale modification of natural conditions. The structural patterns seem predetermined by the active side of the tensed region and by the load factor controlled by topographic slopes. Typical graben were not produced by any of the many variations, within scale limits, which were tried out and are believed to be due to some other sort of force than simple tension.

INTRODUCTION

Tension faults were produced experimentally to determine the form assumed under specific and different conditions. The average strike of these simulated normal faults was perpendicular to the direction of greatest tension, i.e. strike-slip movement was not involved. Experiments were performed on a scale model, greatly reduced from nature. Conditions such as strength, thickness, rate of strain, and surface slope of strata were varied singly and collectively in succeeding tests.

A number of attempts have been made to reproduce deformation of the Earth's crust experimentally. In this, the work of Hans Cloos (1929-1930) is outstanding; his object was to reproduce normal faults, using a scale model. In order that the model simulate natural conditions, the strength of the material representing the rock strata had to be reduced to a degree commensurate with the small size of the model. Therefore Cloos used wet clay, too soft to stand and contained in a box with one end movable, the other fixed. Overlapping metal plates were attached to the fixed and movable ends. The ends were pulled outward, and a fault pattern occurred only above the overlap of the metal plates.

Our experiments were planned to allow the stress distribution within the simulated rock to control the strain surfaces, and avoided the artificial and arbitrary plate junction as an influence. It is recognized in natural settings that basement complex structures occasionally do guide or influence strain surfaces of subsequent deformations in superjacent strata but rarely to such extent as to hold movement or strain to one plane. Distribution of strain in our experimental procedure was attained by using an extensible basal surface rather than a rigid plate.

SCALE SIMULATION

Scale simulation includes first, study of scale theory and second, devising methods to conform with the scale suggested.

General Scale Model Theory

One of the fundamental problems of this experiment was construction of a dynamically correct model that would effectively simulate a portion of the Earth's crust under tensional stress. Hubbert (1937) outlined the essential mechanical properties of any model relative to the known properties of the original and given in terms of the three fundamental model ratios μ, λ, and τ of mass, length, and time.

Definition of these model ratios follows.

μ is equal to the mass of the original divided by the mass of the model.

λ is equal to the length of the original divided by the length of the model.

τ is the ratio of the time consumed in the original process to the time necessary to produce a similar process using a particular scale model.

Aside from these, a number of dependent model ratios are introduced later. As one example, the density ratio δ is equal to $\mu\lambda^{-3}$. It will be noticed that this relationship corresponds closely to the formula $d = m v^{-1}$ where d equals the density of a body, m its mass and v its volume (which is, after all, expressed in cube of length units).

Reynolds (1883) worked out the following equation applying to any fluid. Any characteristic length multiplied by a characteristic velocity η divided by the kinematic viscosity (the viscosity Ψ to density ratio) is equal to R, or Reynolds' number for a particular case. It follows that for a model dynamically similar to the original we get R_2 / R_1 is equal to the product of the length and mass model ratios divided by the kinematic viscosity ratio, which is in turn equal to unity. That is:

$$\frac{R_2}{R_1} = \frac{\lambda\eta}{\Psi/\delta} = \frac{\lambda^2\ \tau^{-1}}{\lambda^2\ \tau^{-1}} = 1$$

Since Reynolds' number is taken from the ratio of the inertia to the resistive forces, it approaches zero when the inertia forces are negligible compared to the resistive forces. In such cases the restriction of the above equation may be violated, and dynamic similarity can still be obtained when the respective Reynolds' numbers are not equal, but both small.

In this case we have as our fundamental ratios: μ and λ, and λ is independent of τ when inertial forces γ are negligible, because the force of gravity is dominant here, and this force is quite independent of the model ratio of time used in a particular experiment. Furthermore $\gamma = 0$ and γ_g (acceleration of gravity ratio) $= 1$ since both our model and the original are at the Earth's surface. The density ratio, $\delta = \mu\lambda^{-3}$, the force ratio $\Phi = \mu\ \gamma_g = \mu$, and the stress and strength ratios (which are the same), $\sigma = \Phi\ \lambda^{-2} = \mu\ \lambda^{-2} = \delta\ \lambda$.

Model Ratios for This Experiment

This model simulates an area of the Earth's crust about 100 to 150 km wide. Since the model is about 40 cm wide, $\lambda = 3 \times 10^5$. The Earth's crust is generally strong enough to support a column 10 to 20 kilometers high. The density of the crust is approximately 2.7 whereas the density of the model is approximately 1.5, giving $\delta = 1.8$. Thus the strength ratio $\sigma = 1.8 \times (3 \times 10^5)$, and the strength of the model material should stand as a column about 2 to 4 cm high. The value in Cloos' experiments was 2 to 4 cm. He described his clay as having "the consistency of thick cream." This experiment made use of wet clay because it is intermediate between plastic and brittle. The rocks composing the Earth's surface are generally brittle but do have plastic quali-

ties under pressure. Furthermore, the stress necessary to produce plastic shear is very nearly independent of the rate of shear.

Independence of Rate of Shear

In theory, and for the purposes of this experiment, the time ratio (τ) is almost an independent variable, which can be modified to suit the convenience of the experimenter. However, in experimental practice, various rates of strain gave varied experimental results. For example, 15 inches per hour rate of strain produced numerous small faults whereas 2.6 inches per hour strain gave larger and less numerous faults. Nevertheless, at 5 inches per hour faults were only slightly smaller than those produced at 2.6 inches per hour, and it is therefore suggested that a 1 inch per hour rate of strain would produce faults very little different in character from the 2.6 inches per hour sort. It is entirely possible that at approximately 1 to 2 inches per hour conditions approximate a critical value of τ beyond which further change in rate (i.e. further decrease in rate of strain) has little effect on experimental results.

EXPERIMENTAL ARRANGEMENT

The apparatus is described below, and the essential controls to permit variation of conditions are outlined briefly.

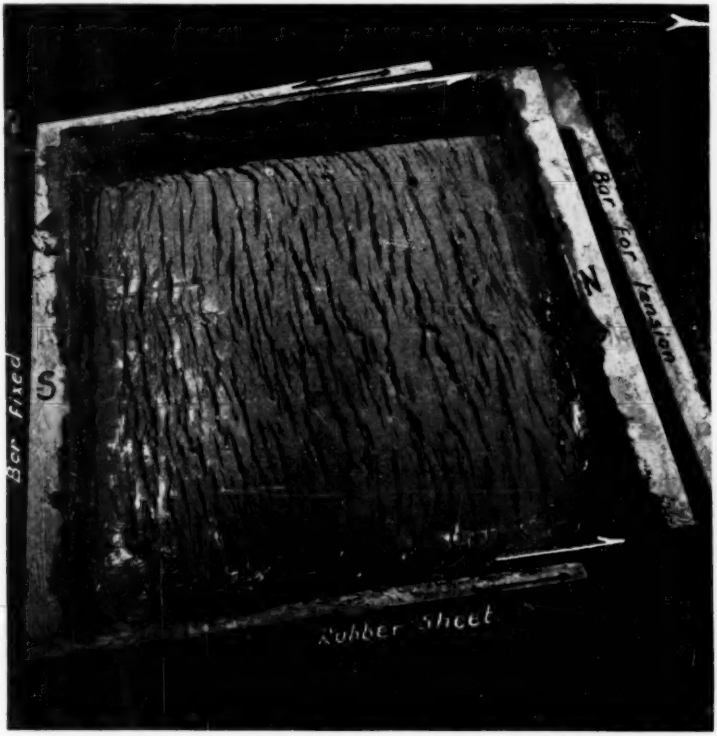

Fig. 1. Photograph showing the extensible container and deformed clay.

Description of Apparatus

The simulated strata, built on a rubber sheet which could be elongated at various uniform rates, were composed of a stiff, creamy, clay-water mixture. The rubber sheet base served as a means of applying a generalized tensional stress to the strata, and a small electric motor provided the motive power.

The arrangement was prepared as follows: A thin rubber sheet of size 2 feet by 2.5 feet was stripped of talc on the top side to cause adhesion of overlying clay to the rubber during the experimental work. The sheet was attached along the longer edges to 3-foot lengths of 1-inch pipes and laid out on a table. A wire was passed through one of the pipes and used to anchor the south end of the sheet. A length of rope passed through the north end pipe, and each end of the rope ran over a pulley to a winding system driven by a 1/20 H.P. gear reduction electric motor. This winding system was the source for a uniform rate of strain. A framework contained the clay and was constructed of two sections, each resembling a box with the bottom and one side missing. The north end of one "semibox" was slightly shorter than the end of the other semibox and formed a sliding fit inside it (fig. 1). This enabled the sides to slide freely, as strain was induced by the motor, yet still retain the clay. Generally, the south end remained fixed during stretching of the clay. Wet clay of the proper consistency was poured into this framework until it occupied a space 26 inches wide, 17 inches along the length of the table and 2.5 centimeters deep. Operation of the motor applied stress to cause uniform rate of strain in the clay.

Control of Rate of Strain

The electric motor ran at 43 r.p.m., and its speed was reduced by worm gears and a cone pulley system. The belt connections in the cone pulleys were used to vary rate of strain. The fastest rate of strain was 12 inches per hour, while the slowest rate was 2.6 inches per hour.

Control of Competency of Strata

Indirect control of clay consistency or competency was accomplished by specific gravity determinations. If the specific gravity in one experimental run was 1.43 and a comparable consistency was desired in a later experiment, the clay could be allowed to dry if too wet, or water could be added and stirred in if too dry, until density was 1.43. Clay was used at specific gravities, varying from 1.398 to 1.467 during the experiments.

FORM OF FAULTS

The average angle of inclination, the direction of inclination and the size of faults varied with thickness and strength of strata, and with the duration and rate of application of stress. The faults assumed a steep dip during the early stages of development but were rotated to angles of less than 45° with continued application of stress. Size of faults increased within limits with increase in thickness and/or strength of strata and decreased with increase in rate of stress application.

Development of Faults under "Normal" Conditions

The faults developed under simplified or "normal" conditions are de-

scribed first. The clay had 1.44 sp.gr., was 2.5 cm deep, its surface was horizontal, and the rate of strain was 2.6 inches per hour.

Minute shears began to appear at the north or mobile side after stress had been applied for about 20 minutes. Strike of these shears, as well as those that developed later, was essentially E-W and perpendicular to the stress axis in the rubber sheet. However, figure 1 shows that the strike is not a straight line and is modified further where stress is transmitted from the sides of the restraining "semiboxes." Similar departures from linear form appear also in actual fault forms. The early shears or faults grew larger as stress was applied uniformly to the rubber sheet and new minute faults began to form. Appearance of initial shears at the north side is attributed to friction between the rubber sheet and the table, aggravated by the pressure of the clay on top of the sheet. This concept is appreciated if one presses down on a rubber band with the palm of one hand, and pulls out an end with the other hand. It will be noticed that the band slips first and is extended under the side of the palm nearest the stress.

Small faults tended to join together as they enlarged and produce one fault where originally two or more had started. Also some faults joined even when they were initiated on different planes slightly offset from each other (fig. 2). Ofttimes the trace of a fault lying northward from a second one joined in with the southerly one producing a single fault with "steps" or angles in its trace and scarp. This phenomenon has been observed also in the field.

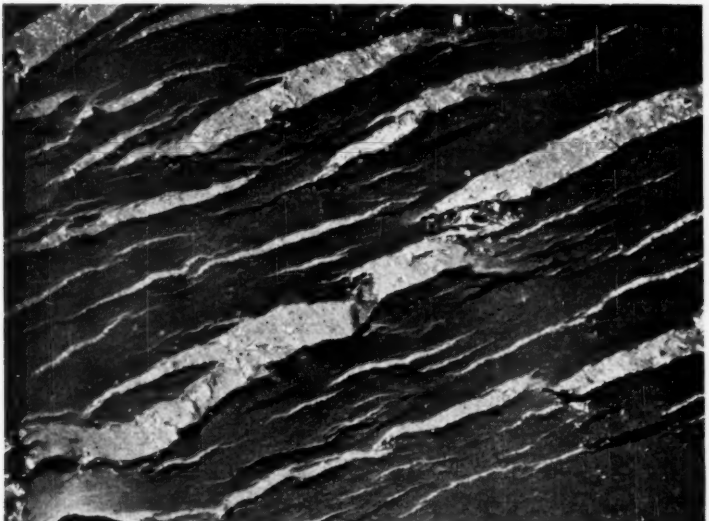

Fig. 2. Photograph showing steps, terminations and offsets in tension faults.

Description of Fault Patterns and Individual Faults

Detailed observations were made of the fault patterns, and the form of faults in the pattern, and close watch was kept for development of graben. Typical graben and horsts did not form as persistent structures under the conditions of the experiments.

Fault patterns.—A definite pattern of faults was obvious after two hours of applied tension which caused 5.2 inches of strain; the features are shown on figure 1. Multiple faults had joined up in many instances; size varied from less than 1 inch long and less than 1 mm high to 10 inches long and throw exceeding even 1/4 inch. The faults dipped about 30° after two hours of stress application, and actual maximum dip-slip was about 1/2 inch. The larger faults were about 0.5 to 1 inch apart, but a number of smaller faults with throw of 1/8 inch generally lay between them. Toward the eastern and western edges of the clay the fault traces swung away from the stress direction in the rubber sheet. This effect was due to stress transmission from the box sides.

The general pattern of the simulated faults corresponds closely to actual basin and range structure. Like the actual case, it lacks numerous graben and horsts which appear in so many idealized representations of this sort of structural province. Experimentally, tensional stress divided the "crust" into blocks separated by uniformly dipping normal faults. Rotation of these blocks, downward on one side and upward on the other, formed "ranges" and "intermontane basins." Initially the faults dipped steeply at about 70°; (this figure is only approximate since the early small faults could not be measured accurately). However, after an hour, the dip of faults was measurable by using a clinometer. Rotation took place as time passed, and the average dip was only

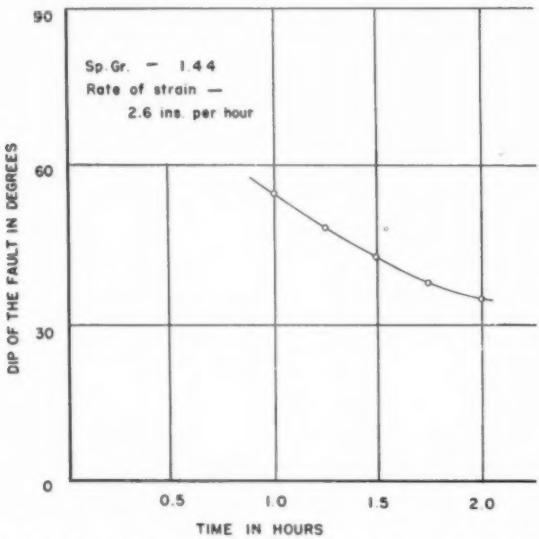

Fig. 3. Graph showing change in fault inclination relative to time or strain increase.

35° after two hours of stress at 2.6 inches per hour (fig. 3). This meant that the reverse slopes of the fault blocks inclined in a direction opposite to the fault dips, giving the basin and range topographic form to the structure.

Fault forms.—Individual simulated faults showed forms that have field counterparts. Displacement of the strata diminished both laterally and in depth during early stages of development. Dip probably changed with depth, although no direct observations were possible beneath the clay surface. However, variation of dip from place to place along the trace of individual faults was measured; one fault 8 inches long had 38° average dip; measurements at 1-inch intervals along the trace gave dips of 36°, 30°, 32°, 25°, 40°, 50°, 54°, showing lowest inclination near the center of the shear.

The faults died out laterally and displacement was not uniform along any given fault, either in direction or magnitude. Indeed strike, dip, and net shift varied along any one fault, exhibiting a condition observed in natural forms.

Slickensides or flutings caused by the movement of the hangingwall against the footwall were obvious on the scarps of the simulated faults. They appeared to be quite similar to slickensides found on the scarps of natural faults.

Graben.—At the outset of the experimental work, it was hoped that the horst and graben type of basin and range structure might be simulated in model form. Generally this did not happen, and the faults all tended to dip in the same direction. However, graben were produced in the early stages of stress when the surface of the clay was essentially horizontal.

The graben development in this model took the following patterns: Twenty minutes of stress application initiated small faults dipping in the same direction. As the hangingwall of each fault began to move downward relative to the footwall, the clay surface of the hangingwall block was rotated slightly and dipped toward the fault scarp. Usually fault planes tend to incline in the same direction as the surface of the strata; often a secondary fault developed in the hangingwall within 1/4 inch from the main fault and dipped toward the latter.

These miniature graben did not continue to enlarge under continued stress application; the original fault of the pair increased in size, whereas the secondary fault grew scarcely at all. Initially, the simulated faults do not extend down to the rubber sheet but extend their surface down gradually as strain increases. Thus the original fault of the pair making the graben extends deeper than the secondary faults at any given time and cuts off the secondary one which terminates against the moving block. Thus only the primary fault continues to grow larger.

EFFECTS DUE TO CHANGE OF VARIABLES

Water content controlling competency, rate of strain, and slope of the surface were varied to determine their effect and, by analogy with field cases, suggest the potential application of experiment to interpretation of structural history.

Water Content

Varying the water content of the clay gave different experimental measurements. A high proportion of water in the clay reduced both specific gravity and strength or competency. Low strength modified the form and spacing of faults from corresponding features encountered in higher strength clay. At the lowest specific gravity used (about 1.40), the faults had low net displacement, and net shift was less than one-fourth that on faults in clay of sp.gr. 1.45. Also dip was less and shear planes were spaced more closely. However, the length of the trace of a fault averaged about the same for any clay density. Thus the height to length ratio was 1/80 at sp.gr. 1.40 and 1/20 at sp.gr. 1.45.

Rate of Strain

Varying the rate of strain had definite effects except when diminished to approach 2.6 inches per hour. Rate of strain at about 15 inches per hour produced faults that had average net shifts appreciably less than those of faults produced in clay of the same competency and at a 2.6 inches per hour strain rate. However, faults produced at 5 inches of strain per hour were only slightly smaller than those produced more slowly. Thus it seemed that the time ratio could be distorted if the rate of strain was slow enough. At speeds appreciably greater than 2.6 inches per hour, faults had smaller net shifts, were more closely spaced, but were nearly as long as slow speed faults. Moreover, many clays of higher competency, producing only tension cracks under fast stress application, sheared instead if the rate of application was reduced adequately.

Slope of Clay Surface

Some of the more interesting phenomena observed in the present experimental work were correlated with slope to the clay surface. Conspicuous slope of the entire clay surface toward the north or toward the south was attended by development of faults under tension which likewise dipped northward (if the surface dipped north) or southward (if the surface dipped south). This behavior recurred regardless of whether the stress itself was applied from the north or from the south. Since this principle operates for a dynamically correct scale model, it should be expected to have some bearing upon interpretation of the record for a sequence of events in a part of the Earth's surface which has been deformed under tensional stress.

It was hoped that by inclining the northern half of the clay toward the south and the southern half toward the north faults would be produced which had dips following their respective slopes, thereby producing graben in the central section. The experimental results were quite different. It has been pointed out already that faults develop first in that part of the clay nearest the side of stress application because of friction effects somewhat comparable to "viscosity" of flow in the so-called asthenosphere. Application of stress to the above "flattened V"-shaped arrangement was attended by appearance of initial faults on the northern (southward-dipping) slope and with fault surfaces inclined to southward. Extension of the faulted zone to southward into

the area of northward-inclined clay witnessed production of shear surfaces which continued to dip southward. The direction of dip of the earliest faults had set a precedent strong enough to cause later faults to dip in the same direction even where the surface slope effect would tend to direct dip in the other direction. The cause for this effect is essentially the same as the one offered to explain why the small graben, which were produced in the model, did not grow into large graben under continued stress. The earlier south-dipping faults were able to block off any attempt by northward-dipping faults to penetrate to depth.

Another arrangement was made in an attempt to produce graben under tensile stress; the possibility of this condition being duplicated in nature suggests to us that graben are produced only rarely by tensile stress. Clay was arranged near the north side of the apparatus to dip gently southward for not more than one-fifth of the total surface area. The other four-fifths of the clay surface dipped northward at almost 20°. The anticipated southward-dipping faults appeared on the gentle slope as stress was applied. However, northward-dipping faults soon began to appear on the steeper northward-dipping slope and soon these became dominant. The original southward-dipping faults increased in size hardly at all and new shears dipping southward appeared on the gentle slope!

These observations suggest that, in the case of a doubly sloping land surface, the dip of all faults will follow the direction of inclination of the slope nearest the stress unless the more distant slope is much steeper and more extensive.

SUMMARY AND CONCLUSIONS

The present experiment used a model somewhat similar to that of Cloos. The overlapping metal plates were replaced by a rubber sheet in order to distribute the strain. Regional basin and range structure, comprised of many individual tension faults, was reproduced by using a clay-water mixture.

Specific conclusions include:

1. Under tensional stress, the clay strata sheared to produce normal faults.
2. A normal, that is, a line perpendicular to any shear surface, inclines downward and outward towards the actively moving side or base of the clay except when the clay thickness was varied systematically as outlined under conclusion 7.
3. Tension cracks resulted when the clay was too strong (dry) and/or when stress was applied too rapidly.
4. Relatively slow rates of strain (2.6 to 5.0 in./hr. produced the largest faults.
5. Initial faults were nearest the source of stress.
6. Faults were steep during early development and rotated to a lesser inclination with continued application of stress.
7. Faults dipped southward or northward (side of stress direction) depending on direction to slope of the clay surface when the thickness

was varied systematically. In general, faults dipped in the same direction as the clay surface.

8. Distributed tensional stress produced graben of small size and only in rare instances.

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THE ROCK AND STONE TERMS LIMESTONE AND MARBLE

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ABSTRACT. The general term *limestone* should be applied to any rock composed of more than 50 percent calcite. Sedimentary limestone can conveniently be designated as such by using the prefix *ortho*, and metamorphic limestone, by using the prefix *meta*. The same prefixes also should be employed to indicate the sedimentary or metamorphic nature of *dolomites*. *Marble* is a commercial term. Limestones and dolomites of low porosity, high degree of purity, and possessing properties imparting commercial value as sources of finished building and ornamental stones are marble. The sedimentary or metamorphic nature of these commercially valuable stones, i.e. marble, can best be indicated by using the same prefixes as for the source rocks.

INTRODUCTION

About 75 percent of the rock quarried, finished and sold as marble in the United States is not marble,[1] according to the prevailing scientific terminology.

The presently accepted scientific definition of marble is that it is a metamorphosed carbonate rock which is composed predominantly of either calcite or dolomite. In the dimension stone trade, however, marble is any carbonate rock which can be promoted commercially as a finished stone for artistic or architectural purposes because of desirable physical properties such as durability, low porosity, and desirable color or color patterns. Some would restrict the term to a carbonate rock which because of its purity, very low percentage of void spaces, and crystalline texture is capable of receiving a high polish, and others would further restrict it to include only the finished stone.

As a result of the loose usage of the word, much confusion has resulted, and the word marble is presently used by most geologists with a qualification or an apology.

A brief historical account of the origin and usage of the words applied to consolidated carbonate rocks is presented in an attempt to arrive at a terminology which will be mutually satisfactory and beneficial to the people in the building trades and to academic geologists. If accepted, it is believed that the proposed compromise presented below will remove a source of misunderstanding between the two fields of endeavor.

ETYMOLOGY AND EARLY USAGE OF THE WORDS MARBLE AND LIMESTONE

According to the students of philology, Sanskrit, the language of the ancient Hindus of India, approximates the hypothetical parent language from which all the Indo-European languages evolved. Interestingly enough, the word in Sanskrit which is akin to the word for marble is the word *mrnati*, which means to grind or crush, and it is apparently the same root from which the word mill arose. In the Greek language, the word for marble is *marmaros* which is related to the verb *marmairein*, meaning to flash, sparkle, glisten or gleam. The Roman scholar, Pliny the Elder (1938, p. 157), used the Latin word *marmor* in his work on natural history completed in 77 A.D. for calcareous building stones and their source rocks. This is essentially the sense

[1] This estimate is based upon production figures for 1950 presented in the Minerals Yearbook, 1953, p. 1151.

in which the French scholar Buffon (1825, v. 7, p. 29) used the term when he wrote, "Le marbre est une pierre calcaire dure et d'un grain fin, souvent colorée et toujours susceptible de poli . . . . " i.e. marble is a fine-grained, durable limestone, often colored and always susceptible of receiving a polish. He mentions recent deposits precipitated from water, i.e. onyx marble, and fossiliferous productions of the sea.

The ruins of ancient cities, ancient inscriptions, and the writings of ancient chroniclers revealed that certain stones, including carbonate rocks, serpentine, porphyries, basalt, granite and syenite, were extensively used by the ancients to build and decorate temples for gods and palaces for kings. Rock that could be easily "milled" for ornamental building purposes became known as marble. Until more was known about the composition of stones, the criteria for the classification of rocks were the more evident physical properties; therefore, many diverse types of finished dimension stones were known as marble. Even today, the variety of beautifully mottled green rock which is quarried, finished and sold as *Verde Antique* "marble," is not a carbonate rock but is composed predominantly of the mineral serpentine, a hydrous magnesium silicate.

The durability and beauty of finished stones processed from the many varieties of nonporous, massive carbonate rocks are seldom exceeded by other harder potential building stones. The ease with which these rocks could be worked led to their extensive use in sculpture and architecture. This facility was of the utmost importance to the classical and medieval craftsmen. Thus, it is believed that the word marble became applied primarily to the carbonate stones because they could be easily "milled."

Common earthy to crystalline rocks composed predominantly of the mineral calcite have been utilized since the dawn of civilization for the production of lime for medicinal, alchemical, and masonry purposes. Upon heating these rocks to a sufficiently high temperature, CO_2 is driven off, and a white powder composed of CaO (lime) is produced. Primitive man therefore looked upon these rocks as a source of lime.

The Latin word for lime is *calx* and it is from this root that the German term *Kalkstein*, the French term *pierre calcaire*, and the English term *chalk* have been derived. In the Anglo-Saxon language, the predecessor of modern English, calcium oxide was called *lim* and thus the common varieties of rock which could be "burned" to produce lime became known as *limestone*.

ORIGIN OF THE SCIENTIFIC TERMINOLOGY

Geologists began to employ the word marble as a scientific term for metamorphosed carbonate rocks during the middle part of the 19th century. This usage was probably the outgrowth of a series of experiments performed by Sir James Hall to prove that sufficiently high confining pressure would prevent calcite from being altered to lime by high temperature (Hall, 1812). Since calcite is found in all types of rocks, these experiments of Hall's were performed to prove or disprove Hutton's theory of the Earth (Hutton, 1788), which proclaimed that crystalline schists, gneisses, granites, etc., had been produced by the action of heat and pressure. Some of the crystalline masses

produced in Hall's experiments with calcium carbonate at high temperatures and confining pressures were sent to a lapidary to be cut and polished. The cut and polished specimens were compared by Hall to natural statuary marble.

Sir Charles Lyell found in Hutton's theory of the igneous origin of crystalline rocks the "germ" of the theory which he elaborated and named the metamorphic theory (Lyell, 1839, p. 21-22). Lyell states (p. 27) that "any limestone which is sufficiently hard to take a fine polish is called marble. Many of these are fossiliferous; but statuary marble, which is also called saccharine limestone, . . . is devoid of fossils, and a member of the metamorphic series." Later on in the text, Lyell discusses metamorphosed carbonate rocks under the subtitle "Hypogene or metamorphic limestone" in a chapter on metamorphic rocks (p. 134). Obviously, Lyell, the founder of the metamorphic theory, did not intend that marble should be a term restricted to metamorphosed carbonate rocks. He used metamorphic limestone as a term for these rocks.

Previous to Lyell, "geologists" used the term primary or primitive limestone for carbonate rocks found in association with slates, schists and gneisses, i.e. *Urkalk* by Werner (Adams, 1938, p. 219) and *pierre calcaire de premiere formation* by Buffon (1825, v. 6, p. 486-498).

PROPOSED TERMINOLOGY

There are three alternatives to choose from in the employment of the word marble in science and in commerce: first, the present loose usage could be continued to the detriment of both science and commerce; secondly, the word could be abandoned by the geologists as an unfortunate ambiguous term and left to the building trades as a term for finished dimension stones and their source rocks; or both the building trades personnel and geologists could make concessions and the word be returned to its classical meaning as a nonporous rock (preferably restricted to carbonate rocks) which has properties imparting desirable characteristics suitable for utilization as a building or ornamental stone.

Relinquishment of the word marble as a general scientific term for metamorphosed carbonate rocks would result in the revival of the term metamorphic limestone as a name for these rocks.

In keeping with the scheme initiated by Paul D. Krynine (1948) to shorten a similar cumbersome binomial terminology for sedimentary and metamorphic quartzites, the prefixes *ortho* and *meta* could be employed. Following this plan, sedimentary limestone would be called *ortholimestone* and metamorphic limestone would be called *metalimestone*. In addition to being euphonic and precise, this terminology would have the advantage of giving recognition to metamorphosed dolomitic rocks. *Metadolomite* until now has been lumped with metalimestone as "marble."

In practice it will probably not be necessary to add the prefix ortho to indicate unmetamorphosed limestones and dolomites since no alteration is implied by the existing usage of these words.

If a deposit of ortholimestone, metalimestone, orthodolomite or metadolomite is nonporous and possesses desirable qualities for building or ornamental stone and if the deposit is of potential commerical value, then the rock could also be termed a marble. For example, the Holston limestone of middle Ordovician age of eastern Tennessee has long been known as the Holston marble since the gray, pink, red and chocolate-colored "Tennessee" marbles are quarried from it (Gordon, 1924). Using the prefixes to designate the sedimentary or metamorphic character of the rock, then this formation more precisely should be termed the Holston ortholimestone and commercially termed the Holston orthomarble at active or prospective quarry sites.

A deposit containing hematite is not an iron ore unless it is accessible and of sufficient concentration so that it can be exploited commercially; likewise, no massive carbonate rock should be termed a marble unless it is a potential source for finished building or ornamental stone.

For the sake of preciseness, the porous hot spring deposit called travertine and the green metamorphosed basic igneous rock called serpentine, which in the past have sometimes been sold as marble, should not be termed marble. The names travertine and serpentine are the appropriate terms for the finished stones produced from these rocks.

The term orthomarble as proposed here would include the "limestone" and "onyx marbles" as discussed by G. W. Bain (1936), and the term metalimestone would include the "crystalline calcite marbles," both statuary and variegated. For a detailed discussion of the petrography of commercial marble, the reader is referred to Bain's excellent article.

CRITERIA FOR DIFFERENTIATION OF ORTHO- AND METALIMESTONE AND MARBLE

It is realized that sedimentary rocks grade imperceptibly into metamorphic rocks as is well exemplified by the rocks of Vermont which have been affected by regional metamorphism. The marbles quarried in the Champlain Valley possess the characteristics of unmetamorphosed limestone, are fossiliferous, and are associated with unmetamorphosed detrital sedimentary rocks. To the east and southeast, the associated detrital rocks gradually change to slates, schists and gneisses, and the carbonate rocks change to crystalline variegated to homogeneous saccharoidal metalimestones (Perkins, 1932, p. 11-51; Bain, 1934). The series of thrust faults called Logan's Line separate the altered from the practically unaltered rocks.

Rocks possess different degrees of susceptibility to metamorphic changes, as is demonstrated by the metamorphosed coal or anthracite associated with relatively unaltered sedimentary sandstones and shales in the Wyoming Valley of Pennsylvania. Like coal, limestone is usually more susceptible to change by metamorphic forces than are the detrital sedimentary rocks with which it is associated. It is true that metalimestone (or metamarble) is usually associated with detritals which have been altered to slates, schists, metaquartzites and gneisses. However, the degree of metamorphism of the associated rocks should not be taken as the sole criterion for the determination of whether a limestone is to be termed an ortholimestone (orthomarble) or a metalimestone (metamarble).

Regardless of the degree of metamorphosis of the associated rocks, to be termed a metalimestone (metamarble), it is the opinion of the author that the internal deformation and recrystallization of the carbonate deposit should have been sufficient to obliterate sedimentary features and fossils. An infallible criterion of metamorphism is the degree of alteration of the noncarbonate impurities in the rock. If the rock has been subjected to agents of metamorphism, the syngenetic impurities such as organic matter, clay, silica, and feldspar will have been changed to graphite, chlorite, mica, actinolite, or other metamorphic minerals.

SUMMARY

Since the dawn of civilization, marble has been a term for building stone. A more general term for rocks composed predominantly of calcium carbonate has been limestone. Attempts of geologists to restrict the term marble to metamorphic limestones have resulted in confusion.

Lyell, the founder of the metamorphic theory, clearly used the word marble for both sedimentary and metamorphic limestones capable of being polished.

It is proposed that the general term limestone be applied to any rock composed of more than 50 percent calcite, and dolomite to any rock composed predominantly of the mineral dolomite. Sedimentary limestone should be termed ortholimestone, and metamorphic limestone should be termed metalimestone. The same prefixes should be used to indicate the sedimentary or metamorphic nature of dolomites.

A carbonate rock of low porosity, high degree of purity, and possessing properties imparting commercial value as a source for finished stone for building and ornamental purposes, could also be termed marble. The sedimentary or metamorphic nature of these commercially valuable rocks should be indicated by using the same prefixes.

ACKNOWLEDGMENTS

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REVIEW

Geologic Map of East Tennessee with Explanatory Text; compiled by JOHN RODGERS. Tennessee Division of Geology Bulletin 58, Part 2. Nashville, 1953 (text and folded maps, $3.50; folio of maps only, $2.50).—Between 1890 and 1907 Arthur Keith, C. W. Hayes, and M. R. Campbell mapped the geology of most of East Tennessee for the folio series of the U. S. Geological Survey. Despite the scale of 1/125,000 and contour interval of 100 feet their product was excellent. Naturally, they made some classic errors, as the mapping was done without benefit of paleontology. Within more recent years the region has been mapped topographically by the Tennessee Valley Authority and the U. S. Geological Survey with scale of 1/24,000 and contour interval of 20 feet. These maps opened a new era for the mapping of the geology of East Tennessee.

The author of the present publication had the cooperative assistance of members of the Geologic Branch of the Tennessee Valley Authority, the U. S. Geological Survey, Tennessee Division of Geology, U. S. Soil Survey, Department of Geology of the University of Tennessee, and the zinc companies operating in East Tennessee. From work done by these organizations and from work done by the author, he has compiled a complete geologic map of East Tennessee. He warns, however: "The chief danger in such a procedure is, of course, that the resulting map will appear much more accurate than it really is. No one is so well aware of its weak points and imperfections as its compilor, and he wishes to issue a general warning to all not to accept it without caution. This map is not a final summing up of the areal geology of East Tennessee, but a progress report. . . ."

As the author states, "A geologic map is no better than the units used. . . ." The units used are of necessity fundamentally rock units, and will be subject to revision as the story told by the fossils is interpreted.

As it seems to be part of the role of a reviewer to find a few things with which to needle the author, the reviewer completes his job. In regard to the title, his own interpretation is that what has been published is the "Geology of East Tennessee with accompanying geologic maps," rather than "Geologic map of East Tennessee with explanatory text." The Bulletin is Part 2. The reviewer anxiously awaits being told the nature, fate, and future of Part 1. In pages 11 to 20 under Physical Geography the author quite understandably quotes Safford. The paragraphs quoted alternate with paragraphs from John Rodgers without any typographical change, making it difficult for the reader to realize when he is hearing the voice of Safford or the voice of Rodgers. The abbreviations of quadrangle names, set off in parentheses (Cleve., Loud., and Ashe.), is annoying to this reader. The writer is sure that Marius R. Campbell would have preferred his own first initial "M" to the "H" of page 3.

The text consists of four major parts, Physical Geography, Description of Rock Units, Larger Structural Features, and Source Materials and Outstanding Future Projects. Fourteen geologic maps with scale of 1/125,000 and a plate of cross-sections are folded in the map container. The Bulletin is an outstanding contribution to the Geology of Tennessee, and the author and the Tennessee Division of Geology are both congratulated and thanked.

CHARLES W. WILSON, JR.

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